Tomi Nukarinen

Assisting Navigation and Object Selection with Vibrotactile Cues

ACADEMIC DISSERTATION
To be presented, with the permission of the Faculty of Information Technology and Communication Sciences of Tampere University, for public discussion in the Pinni B5103 Campus Chapel on March 7th, 2019, at noon.

Faculty of Information Technology and Communication Sciences
Tampere University

Dissertations in Interactive Technology, Number 30
Tampere 2019

ACADEMIC DISSERTATION IN INTERACTIVE TECHNOLOGY

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ISBN 978-952-03-1005-9 (pdf)
http://urn.fi/URN:ISBN: 978-952-03-1005-9

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

Dissertations in Interactive Technology, Number 30

Faculty of Information Technology and Communication Sciences
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ISBN 978-952-03-1004-2 (print)
ISSN 1795-9489

PunaMusta Oy – Yliopistopaino
Tampere 2019

Abstract

Our lives have been drastically altered by information technology in the last decades, leading to evolutionary mismatches between human traits and the modern environment. One particular mismatch occurs when visually demanding information technology overloads the perceptual, cognitive or motor capabilities of the human nervous system. This information overload could be partly alleviated by complementing visual interaction with haptics.

The primary aim of this thesis was to investigate how to assist movement control with vibrotactile cues. Vibrotactile cues refer to technology-mediated vibrotactile signals that notify users of perceptual events, propose users to make decisions, and give users feedback from actions. To explore vibrotactile cues, we carried out five experiments in two contexts of movement control: navigation and object selection. The goal was to find ways to reduce information load in these tasks, thus helping users to accomplish the tasks more effectively. We employed measurements such as reaction times, error rates, and task completion times. We also used subjective rating scales, short interviews, and free-form participant comments to assess the vibrotactile assisted interactive systems.

The findings of this thesis can be summarized as follows. First, if the context of movement control allows the use of both feedback and feedforward cues, feedback cues are a reasonable first option. Second, when using vibrotactile feedforward cues, using low-level abstractions and supporting the interaction with other modalities can keep the information load as low as possible. Third, the temple area is a feasible actuation location for vibrotactile cues in movement control, including navigation cues and object selection cues with head turns. However, the usability of the area depends on contextual factors such as spatial congruency, the actuation device, and the pace of the interaction task.

Acknowledgements

First, I thank Professor Roope Raisamo. My journey into academic research began when he offered me a research internship in 2011, something that came by surprise at the time. Through the years, Roope has provided me independence to navigate freely in HCI research while also giving support when obstacles have arisen. I also thank Professor Veikko Surakka. I feel that taking Veikko's course Human Factors in Interactive Technology in 2009 had a significant impact on how I ended up half computer scientist, half psychologist. Furthermore, I thank my co-authors, this work would not exist without you.

Further, I thank the Finnish Funding Agency for Innovation (Tekes), Business Finland, and the associated project partners for funding the research for the five experiments. Additionally, I thank the financial support from the Faculty of Communication Sciences. The dedicated funding made it possible to achieve a relaxed mindset for writing the thesis.

Finally, I thank my family for maintaining a supportive attitude towards my education while not pressuring me in any particular direction.

Tampere, December 12, 2018

Tomi Nukarinen

Contents

List of Publications

This dissertation is composed of a summary and the following original publications, reproduced here by permission.

The Author’s Contribution to the Publications

All of the papers in this thesis were co-authored with at least three other authors. However, the present author had the main responsibility for each of the publications. Further, the present author carried out all of the work apart from the parts mentioned in the following.

In the first publication, the initial idea for the novel interaction technique came from Roope Raisamo. Additionally, Johannes Pystynen implemented the pilot experiment for the work. Erno Mäkinen and Johan Kildal provided comments on the paper draft. Roope Raisamo also had a supervisory and editorial role in the publication. The present author had the main responsibility for analyzing the experimental data and writing the publication.

In publication II, Ahmed Farooq and Grigori Evreinov provided the haptic seat prototype for the experiments. Ahmed Farooq also commented the paper draft. Roope Raisamo and Veikko Surakka had supervisory and editorial roles in the publication. The present author implemented the user experiment, carried out data analysis, and had the main responsibility for writing the publication.

In publication III, Jussi Rantala was responsible for providing the haptic glasses prototype while Ahmed Farooq was responsible for the haptic seat prototype. Both also commented the paper draft. Roope Raisamo had a supervisory and editorial role in the publication. The present author was responsible for implementing the user experiment, carrying out data analysis, and writing the publication.

In publication IV, Jari Kangas had a substantial role as the second author in data analysis and writing the paper draft. Oleg Špakov, Poika Isokoski, Deepak Akkil, and Jussi Rantala gave comments on the paper draft. Roope Raisamo had a supervisory and editorial role in in the publication. The present author implemented the user experiment, carried out most of the data analysis, and had the main responsibility for writing the publication.

In publication V, Jari Kangas had a significant role in data analysis and writing the article draft. Jussi Rantala and Toni Pakkanen provided comments on the article draft. Roope Raisamo had a supervisory and editorial role in in the publication. The present author was responsible for implementing the user experiment, carrying out most of the data analysis, and writing the publication.

1 Introduction

Modern life has been drastically altered by information technology in the last decades, for instance, by mobile phones, internet, and social media. This rapid change seems to have led to an evolutionary mismatch between our traits and the modern environment. For instance, mobile devices are likely to undermine the ability for sustained focus (Oulasvirta, Tamminen, Roto, Kuorelahti, 2005). Traffic accidents are one of the more visible results of impaired attention (Madden and Rainie, 2010). On a more general level, this information overload appears to lead to a worsened ability to make decisions (Buchanan & Kock, 2001; Vohs et al., 2014).

I propose that unraveling questions related to information overload is of great importance in human-technology interaction; in other words, solving evolutionary mismatches. Our attentional capacity is a bottleneck in information processing (e.g., Marois & Ivanoff, 2005), and attention seems to be an invaluable asset in an information society. Thus, any technology that reduces the demands on attention may be highly beneficial.

The term *haptics* refers to sensory and motor activity based on the skin, muscles, joints, and tendons (ISO, 2009). Complementing visually heavy interaction with technology-mediated haptics could be one solution to alleviating the information overload. Haptic communication can decrease visual load in stressful environments in particular (Payette et al., 1996). Studies have also demonstrated that combining visual feedback with haptic feedback improves performance (Burke et al., 2006; Prewett, Elliott, Walvoord, & Coovert, 2012). By including haptics, we can design more effective human-technology interactions than would be possible with merely visual-auditory information.

While supporting interaction with suitable haptic displays may decrease sensory load in the visual channel, technology alone will not solve problems. More importantly, the haptic technologies have to respect the physical, affective, cognitive and social needs of humans: i.e., be adaptive, intuitive, and avoid evolutionary mismatches. However, we are still in the early stages of the scientific systematization of haptics and touch interaction (e.g., Raisamo et al., 2009; Lumpkin, Marshall, & Nelson, 2010; Gallace & Spence, 2014). Also, human-computer interaction as a field appears to lack integrative concepts, theories, and methods (Oulasvirta & Hornbæk, 2016). Thus, there is plenty of uncharted territory in human-technology interaction, haptics included.

1.1 OBJECTIVE

The purpose of the thesis was to investigate **how to assist navigation and object selection in human-technology interaction with vibrotactile cues**. The primary aim was to find ways to reduce information load in these contexts of movement control, thus helping users to reach goals effectively. We conducted five experiments for this purpose.

With movement control, I refer to *voluntary, coordinated movements that humans perform in interaction with the environment.* Navigation and object selection can be both described as motor control (Latash, Levin, Scholz, & Schöner, 2010) processes. The main difference is that compared to object selection, navigation often concerns longer distances in time and/or space.

With vibrotactile cues, I relate to three types of technology-mediated vibrotactile signals. First, a vibrotactile cue refers to *a feedforward signal that notifies a user that some perceptual event has occurred*. The cue prompts decision. For instance, a vibrating phone suggests that the incident demands decision-making but does not imply either answering or ignoring the event. Second, a vibrotactile cue also refers to *a feedforward signal that proposes the user to make a decision*. The cue prompts action. For example, a vibrating driver's seat can imply that the driver should turn in the hinted direction if s/he wants to reach a particular destination. Third, a vibrotactile cue also refers to *a signal that gives the user feedback from an action*. The cue prompts perception. For instance, a vibrating game controller can assure a user that s/he has hit the desired target in a game.

We investigated decision to action cues in experiments one, two, three, and action to perception cues in experiments one, four and five. More specifically, we studied how vibrotactile cues with particular spatiotemporal parameters affect the interaction between users and technology. Along with comparisons to visual cues, it seemed worthwhile to focus the studies on these two parameters as many consider them to be the most promising for encoding information in tactile displays (e.g., Jones & Sarter, 2008).

1.2 Context

The theoretical context used to approach the topic was a cybernetic systems theory (e.g., Wiener, 1948; Bateson, 1979) perspective. From this perspective, humans and technology form context-dependent, dynamic communication systems with the human aiming to minimize error against a reference point, i.e., a goal.

Further, I take a multiple model perspective to the research topic, implying that any single point of view is too narrow to grasp the complexity of interactive systems. For example, researchers often describe human perception as a bottom-up process (e.g., Gibson, 1966), from the sense organs to the brain. However, perceptual systems also operate top-down (e.g., Miller, Galanter, & Pribram, 1986; Pribram, 1991), and in parallel between the senses (e.g., Ro, Ellmore, & Beauchamp, 2012). Moreover, emotions and cognitions are continuously interacting during most mental activities (Ciompi & Panksepp, 2005). Therefore, to gain a meaningful understanding of human-technology interaction, it is essential to use a transdisciplinary approach with multiple perspectives.

The empirical context of this thesis was vibrotactile technology in multimodal human-technology interaction. More specifically, we explored movement control: navigation in the first three experiments and object selection in experiments four and five. In both contexts, users performed voluntary actions to move towards a goal relying mainly on the visual sense. The aim was to provide the users with task-relevant information using simple vibrotactile cues. Concerning technology, linear vibrotactile actuators were the best match with this aim, and we employed them in four of the five studies, excluding the first experiment with an integrated eccentric rotating mass actuator (ERM) inside a mobile phone. The studies included four use cases: vibrotactile cues in pedestrian navigation, car navigation, object selection by head movement, and object selection by hand movement. The first study examined the difference between vibrotactile decision-action and action-perception cues in pedestrian navigation. The experiments two and three investigated if spatially congruent vibrotactile cues suggesting a decision could assist navigation performance in comparison to visual cues. The studies four and five explored if vibrotactile cues could aid movement control by providing feedback from the user's actions in an eye tracking application and virtual reality.

1.3 Methodology

Each experiment began by identifying a specific movement control issue in current human-technology interaction. For instance, in the navigation studies, this was the visual disruption caused by a conventional navigator. The next step was to come up with potential ways to assist the interaction with vibrotactile cues and to start building an experimental setup for testing the solutions. In every case, this was an iterative process, involving software and hardware development, self-experimentation and pilot tests.

After preparing the experimental setup, the next phase included testing the setup with voluntary participants. All study participants were members of the university community, both staff, and students. We carried out all of the five experiments in a laboratory setting between the years 2011-2017.

We used both quantitative and qualitative methods for assessing the interactions between the participants and the interactive systems. Quantitative methods included measuring reaction times, error rates, and task completion times with computer logs. Quantitative methods also included rating scales to measure the more subjective aspects of the interaction. Qualitative methods consisted of interviews and free-form participant comments concerning interaction.

1.4 Structure

This thesis consists of a summary of the research topic and five individual articles published in five peer-reviewed conferences. In Chapter 1, I introduce the dissertation, summarizing the objective, context, and methodology of the work. In Chapter 2, I focus on clarifying the concepts of interaction and technology and then indicate the problem. After that, I discuss touch perception in Chapter 3. In Chapter 4, I present practical viewpoints into designing vibrotactile cues: perceptual capabilities of the nervous system, actuator technologies, and interaction environment. In Chapter 5, I introduce the five experiments and their results. In Chapter 6, I appraise the findings of the individual studies together. Finally, I summarize the contributions of the work in Chapter 7.

2 Interaction and Technology: Establishing the Problem

While the subject of the thesis is more closely related to haptic interaction than interaction in general, it is not meaningful to try to understand haptic interaction in isolation (e.g., Gallace & Spence, 2014). Perception relies on the integration of information from multiple modalities (Ernst & Bülthoff, 2014), and in practice, interaction is always multimodal. Multimodality was also a central theme in the experiments conducted for the thesis. Thus, in this Chapter, I begin by defining interaction and then proceed to discuss a major problem of current human-technology interaction: information overload.

2.1 MULTIPLE MODELS

There appears to be no agreed-upon definition of interaction although the term is field-defining in human-computer interaction (HCI) or human-technology interaction (HTI). Perhaps this illustrates the complexity of the topic. Researchers have formed at least seven concepts of interaction that are relevant for HCI (Hornbæk & Oulasvirta, 2017). The seven concepts include interaction as a dialogue (Nickerson, Elkind, and Carbonell, 1968), transmission of information (Fitts, 1954), tool use (Baber, 2003), and optimal behavior (Gershman, Horvitz, & Tenenbaum, 2015). Further, they incorporate interaction as embodiment (Dourish, 2004), experience (Hassenzahl & Tractinsky, 2006) and control (Jagacinski & Flach, 2003).

To briefly summarize the views, the dialogue view sees interaction as a cyclic process of communication acts and their interpretations. In the transmission view, interaction means sending messages over noisy channels. The tool view conceptualizes interaction as manipulating the world with tools. Optimal behavior view sees interaction as adapting behavior to goals. Embodiment view presents interaction as contextual acting and being in the material and social world. Experience view interprets interaction as a continuous stream of expectations, feelings, and memories. Finally, control view presents interaction as a process aiming at minimization of error against a reference point. These views seem to offer somewhat different perspectives on the underlying phenomena, each with their specific emphasis, strengths, and limitations.

I propose that a sensible model of interaction has to fulfill at least the following three criteria. First, the model has to include both internal and external descriptions of the interactors. For instance, the tool use view may overemphasize external behavior while the experience view may overemphasize internal feelings. Second, interaction context should receive high emphasis in the model since information is only meaningful within a specific context. For example, typical formulations of the transmission view ignore the context of the interaction. Third, the model should contain direct references to the functioning of the human nervous system when describing the interaction process. Not all of the models of interaction stress this.

2.2 DEFINING INTERACTION

The following definition of interaction builds on the principle that the fundamental building block of the nervous system is a feedback loop (Wiener, 1948). This perspective is part of the control view of interaction (Wiener, 1948; Jagacinski & Flach, 2003). However, I also think the transmission of information (Shannon & Weaver, 1949; Fitts, 1954) and embodiment (Dourish, 2004) views of interaction complement the control view, emphasizing information transfer and the significance of context. The remaining views of interaction, i.e., dialogue, tool view, optimal behavior, and experience can also be seen as compatible with the following formulation, but receive less emphasis here.

Thus, I define interaction as *a contextual, goal-oriented process of decoding, interpreting and encoding information*. Goal orientation means striving to remove an incongruity between an inner mental presentation and an outcome in the outer environment: minimizing error against a reference point. I follow Shannon's definition of information as a reduction of uncertainty (Shannon & Weaver, 1949; Zimmerman, 1989); information is a difference that makes a difference (Bateson, 1979).

Further, information is context dependent and requires a sampling of patterns, gestalts, or forms within a specific context, best described by sampling theory (Pribram, 2013). Dey & Abowd (1999) defined context as *any information that can be used to characterize the situation of an entity*; Bateson (1979) defined it as *transference from past learning*. Thus, an interactive process is not reducible to a passive event of sending and receiving or decoding and encoding information. Instead, interaction is an active process, depending on the previous experiences and attitudes of the subject. In other words, perception is a function of the perceiver, and depends on the questions, probes, and theories that we impose on reality (Felin, Koenderin, & Krueger, 2017). For instance, Llinás (2001) argues that the whole purpose of the brain is contextual decision making based on prior experience. Quantum models of cognition (Busemeyer & Bruza, 2012; Weingarten, Doraiswamy & Fisher, 2016) characterize this interpretative phase as an indefinite state where the outcome is not yet determined. Subjectively, we can experience this state as indecision, conflict, or ambiguity (Busemeyer & Bruza, 2012).

I suggest that interaction, in general, can be described with a three-phase division: *physiological decoding, subjective interpretation, and behavioral encoding* (Figure 1). For instance, perception-decision-action loop is part of the interface theory of perception (Hoffman, Singh, & Prakash, 2015), and the Prenav model proposed by van Erp (2007). Similar stages, named perception, cognition, and responding, can also be found in Wickens' multiple resource theory (2002). Also, Schramm's (1954) model of communication divides communication into three phases: decoding, interpretation, and encoding. Finally, a three-phase division is used in emotion research, containing physiological reactions, subjective feelings, and behavioral expression (Gross, 2010).

In the current definition, physiological decoding covers the transduction and processing of stimuli by sense organs to produce perceptions. Subjective interpretation contains the context-based memories, theories, heuristics, and rules used for predicting the intended semantic meaning of the messages to make adaptive decisions. Finally, behavioral encoding involves sending messages from the brain to the muscles to act or inhibit action. Action, in turn, closes the feedback loop by affecting subsequent decoding.

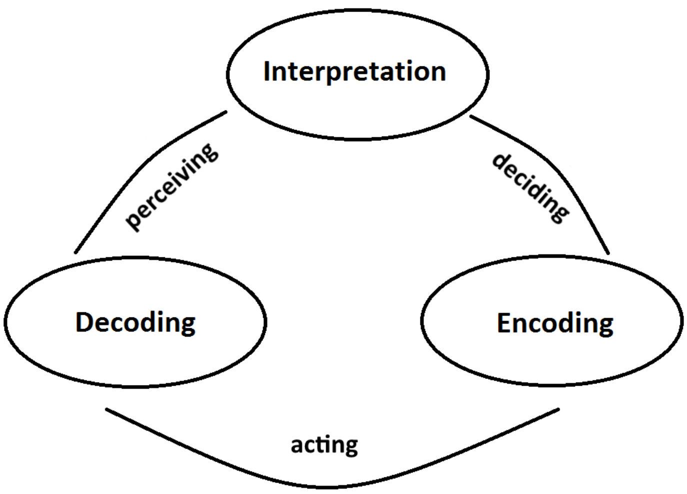

Figure 1. The perception-decision-action loop

Defining interaction as a contextual, goal-oriented process of decoding, interpreting and encoding information can benefit us in the three ways that I suggested are important for an interaction model. First, it seems beneficial to fully acknowledge both the subjective and objective-intersubjective nature of interactive processes. Second, the definition emphasizes the context of the interaction, which is essential as information is only meaningful within a context. Third, the definition ties directly to the functioning of the human nervous system (e.g., Miller, Galanter, & Pribram, 1986; Barsalou, 2008; Pribram, 2013). In sum, the definition provides an integrated meta-view to interaction.

2.3 HUMAN-TECHNOLOGY INTERACTION

Computer scientists, IT engineers and psychologists often use terms such as human-computer interaction, or human-technology interaction when describing the relations between humans and information technology devices (e.g., MacKenzie, 2012). And, as the name of this thesis suggests, the topic we are discussing is how to assist human-technology interaction. One may then ask how technology fits the definition of interaction as a contextual, goal-oriented process of decoding, interpreting and encoding information. It may seem that this perspective to interaction is strictly human-centered.

The view taken here is that by understanding how the human nervous system communicates within itself, a designer can design human-technology interaction to suit the physical, affective, cognitive and social needs of humans; or in other words, design adaptive interaction. The term human-technology interaction may now seem slightly misleading as it gives the impression that human and technology are equal partners in the interaction process. Perhaps a more accurate term would be *technologically enhanced human interaction*. For example, vibrotactile cues can augment human capabilities by providing navigation information on the skin. This description hints that technology is a tool working in the background, helping humans to achieve their goals, not an individual entity demanding attention. Computers should be part of the human interaction loop rather than the other way around (Waibel, Steusloff, Stiefelhagen, & Watson, 2009). In a way, technology acts as an environmental extension of the human nervous system. In this thesis, human-technology interaction is incorporated in this meaning, referring to the augmentation of human interaction with technology.

2.4 Information overload: a human-technology interaction mismatch

Information overload appears to be one of the major problems of human-technology-interaction. Furthermore, reducing information load in movement control with vibrotactile cues was the motivation for this thesis. Information overload refers vaguely to exposure to too much data at once, but we can also reach a more accurate definition. If we divide interaction into decoding, interpretation, and encoding, it would be plausible that a different bottleneck in information processing would affect each phase. The phenomena of attentional blink, limited short-term memory, and psychological refractory period (Marois & Ivanoff, 2005) support this division. The first bottleneck is the phenomena of attentional blink, e.g., when people are shown two targets within 500 ms of each other, they are often unable to perceive the second one (Shapiro, Raymond, & Amell, 1997). Thus, the phenomena can be seen mainly as a problem of decoding and perception. The second bottleneck is that a restricted number of stimuli can be held simultaneously in short-term memory (often referred to as the seven, plus or minus two rule, Miller, 1956). Therefore, this bottleneck affects interpretation and decision making the most. The third bottleneck is the psychological refractory period (Welford, 1952), meaning that when we present two stimuli in a series, an observer's response to the second stimuli tends to come several hundred milliseconds late. Thus, this bottleneck affects encoding decisions into actions the most.

When technology overloads these information processing bottlenecks, multiple issues emerge. Research into multitasking vividly demonstrates these problems: multitasking is defined here as *trying to perform two tasks simultaneously or performing multiple tasks in rapid succession*. Another way to conceptualize multitasking is as *rapid switches in the context of information processing*. Multitasking leads to fragmentation of attention, in which conflicting goals make demands on the perception-decision-action loop. Based on the three-phase model, we can argue that multitasking may lead to failures of perception, interpretation, and action, e.g., distraction, misinterpretation, and slowness.

Research has shown that multitasking can impair learning (Foerde, Knowlton & Poldrack, 2006), cause physiological stress, and affect mood negatively (Wetherell & Carter, 2014). Furthermore, multitasking can be addicting: for instance, while turning phone notifications off can increase productivity, it can also result in anxiety and loneliness (Pielot, 2016). Concerning addiction, it seems quite telling that in 2014, an average college student in the US spent 8 – 10 hours a day using a smartphone (Roberts, Yaya, & Manolis, 2014).

Further, brain imaging studies have associated multitasking with structural changes in the brain, more specifically, smaller gray-matter density in the anterior cingulate (Loh & Kanai, 2014). Researchers have argued that this area is important for regulating cognition and emotions by attention (Bush, Luu & Posner, 2000). Correspondingly, heavy multitaskers are more susceptible to interference from irrelevant stimuli and memories, and also seem to have a worse task-switching ability (Ophir, Nass, & Wagner, 2009). By overloading the limited capacities for self-control (e.g., Muraven & Baumeister, 2000), information overload appears to lead to an impaired ability to make decisions (Buchanan & Kock, 2001; Vohs et al., 2014).

While multitasking is widespread in our society, mobile technology, in particular, seems to encourage it. One study showed that interaction with a mobile device fragmented attention to 4-8 seconds bursts, e.g., 4 seconds on a busy street, and 8 seconds in a cafeteria (Oulasvirta, Tamminen, Roto, & Kuorelahti, 2005). The number of attention switches away from the mobile device reflected a similar trend, approximating eight switches on a busy street and four in a cafeteria (average task length was 16,2 seconds). Accordingly, mobile phone use is the most common distraction among drivers (Klauer et al., 2006). Distraction can also affect pedestrians as mobile phone related pedestrian injuries have exceeded those of drivers in 2010 (Nasar & Troyer, 2013).

Multitasking is also a problem in more static environments: for instance, one study showed that the average length of an event was slightly over three minutes for information workers in an office setting (González & Mark, 2004). It appears reasonable to assume that technology, encouraging multitasking, leads to problems related to information overload in a wide range of contexts. Life-threatening accidents are one of the most hazardous consequences of information overload. However, this may be only the tip of the iceberg. Humans have not adapted to habitual multitasking and the subsequent information overload. One general outcome could be a widespread failure to contextualize information. The ultimate aim of this thesis was to investigate how vibrotactile cues can influence the problem of information overload facing our society.

2.5 SUMMARY

In this Chapter, I identified previously given definitions for interaction. Further, based on these definitions, I formulated a novel definition for interaction: *a contextual, goal-oriented process of decoding, interpreting and encoding information*. Then I proceeded to state that human-technology interactions should emphasize the human part of the interaction. Finally, I introduced a major problem in human-technology interaction, information overload, which is caused by bottlenecks in information processing. Further, I discussed multitasking research that demonstrates the issues which occur when information-processing bottlenecks are overloaded.

In the next Chapter, I will discuss theoretical perspectives of touch perception. I will consider bottom-up, parallel, and top-down processes in touch interaction. I present an anatomical model of touch perception, as well as a psychophysical model. Further, I will mention the role of the subconscious mind and emotions in perception.

3 Theoretical Perspectives to Touch

In the scientific literature, the term haptics is often used to refer to the sense of touch. According to an ISO definition (ISO, 2009), haptics refers to *the sensory and motor activity based on the skin, muscles, joints, and tendons*. In other words, haptics has two main components: cutaneous perception and kinesthetic perception (van Erp et al., 2010). Gibson (1966) included both of these components in his definition, defining the haptic system as *the sensibility of the individual to the world adjacent to his body by use of his body*. I will next describe the haptic system in respect of bottom-up, parallel and top-down processes, emphasizing the sensory side of the interaction.

3.1 PERCEIVING TOUCH: BOTTOM-UP PROCESSES

A bottom-up model may provide the most rudimentary understanding of touch. Therefore, I will first describe a three-tier anatomical model of touch perception, including the receptors in the skin, the sensory nervous system, and the brain. The presented model mainly covers touch perception, not including a precise description of the motor activity, another one of the two major components of the somatosensory system (Dijkerman & De Haan, 2007). After presenting the model, I will shortly discuss the psychophysics of touch, describing the mathematical relationships between physical stimuli and subjective perception.

An anatomical model of touch perception

In the first phase of touch perception, tactile receptors in the skin are continuously sampling environmental stimuli to detect differences in the environment. This sampling occurs in different types of receptors in different parts of the skin: Pacinian corpuscles, Ruffini's end organs, Meissner's corpuscles, Merkel's disks, free nerve endings, and hair follicle receptors (Iggo & Andres, 1982; Kandel, Schwartz, & Jessell, 2000). The receptors differ, among other things, in their body area, adaptation speed, preferred stimulus frequency, receptive field size, and produced sensations (Bear Connors, & Paradiso, 2007; Gallace & Spence, 2014). In particular, Pacinian (200-300 Hz) and Meissner's corpuscles (50 Hz) are important for sensing vibrations (Gallace & Spence, 2014).

When receptors have sampled a stimulus (e.g., a vibrotactile cue) that exceeds the sensory threshold, the sensory nervous system transfers information from the receptors to the brain through nerve fibers. The fibers differ mostly in the speed by which they transmit the neural signals, for which the fiber's diameter is a significant contributor (Hursh, 1939; Tackmann, Spalka, & Oginszus, 1976). The fibers conduct the neural stimuli to the brain through three specific pathways: the dorsal column-medial lemniscal, the anterolateral system, and the somatosensory pathways to the cerebellum (Gallace & Spence, 2014). The anterolateral system transmits pain and temperature information while the cerebellum pathways concern mainly proprioceptive information (Patestas & Gartner, 2016). The dorsal column-medial lemniscal pathway, on the other hand, is used for tactile, vibratory, and proprioceptive information. The transmission time of the information depends on the body location. For instance, the time is around 35 milliseconds from a toe to the brain and approximately five milliseconds from the nose to the brain (Vroomen & Keetels, 2010).

In general, information goes through transformations each time it passes through a set of synapses, and inhibitory interactions between inputs enhance the responses to tactile stimuli (Bear Connors, & Paradiso, 2007). Thus, what will finally reach the brain, does not contain the same information as the initial stimulus. In the third phase, when the transduced stimulus reaches the brain, it is first processed in the thalamus, and then in the primary somatosensory cortex (Bear Connors, & Paradiso, 2007). The perception of touch then results from the integration of multiple inputs into one modality (Saal and Bensmaia, 2014).

After thalamic and somatosensory processing, the touch perception is processed for its semantic meaning based on the interpretation context, consciously or subconsciously. Hippocampus and the left brain hemisphere seem crucial in processing the cognitive part of the meaning; amygdala and the right hemisphere in processing the affective part (Pribram, 2013). Processing in the higher-order brain systems could lead to a continuum of positive and negative emotions, indifference, action or action inhibition. Finally, if the person decides to act, action encoding neural impulses are carried from the primary motor cortex to the muscles. These movement control impulses then provide feedback for the skin receptors, thus closing the feedback loop.

The well-known electrochemical pathways described above may not be the only communication networks in touch perception. For instance, optical communication with biophotons may have a role in information transmission in the brain (Kumar et al., 2016; Zarkeshian et al., 2017). This kind of quantum entanglement phenomenon (Horodecki, Horodecki, Horodecki, & Horodecki, 2009) could also explain how single conscious experience can arise from the activities of billions of neurons that otherwise employ relatively slow transmission mechanisms. At present, the specific role of the optical communication channels in touch perception remains a question.

A psychophysical model of touch

While the previous model provided an anatomical view into touch perception, psychophysics describes the mathematical relationships between physical stimuli and subjective perception. In brief, we make interpretations from a subjective reference point (Helson, 1964). To provide an example, consider that your left hand is in 0 °C water and your right hand is in 40 °C water. If you now put your hands in room temperature water (20 °C), the sensations in your left and right hand do not represent any absolute temperature but a relative change from the previously sampled reference point. Relative to the previous temperature, the temperature in your left hand's sampling receptors is rapidly increasing, and the temperature in your right hand's sampling receptors is rapidly decreasing. Thus, the left hand will feel warm, and the right hand will feel cold.

In general, researchers have studied reference points in a wide range of fields, such as perception, affectivity, learning, cognition and interpersonal relations (Helson, 1964). Historically, Gustav Fechner formulated the idea of a reference point into Weber's law in the 1800's (Gescheider, 1976):

$$\frac{\Delta I}{I} = k$$

In the formula, I is the original intensity of a particular stimulation, ΔI is the addition to it required for the change to be perceived (the just noticeable difference or JND), and *k* is a constant. In a single event, perceived change in stimuli is proportional to the initial stimuli. For instance, when a person compares two values of the same perceivable quantity (e.g., weight), there will be a threshold (ΔI or JND) below which the person cannot consciously discriminate between the quantities. This threshold of difference will be a ratio, and this ratio will be constant over a wide range of values. For instance, if a person can discriminate the perceived weights of 40 grams and 50 grams (a ratio of 4:5), then the person will also discriminate between 400 grams and 500 grams.

Weber's law was dominant for a century before psychologist Stanley Stevens formulated the Stevens' power law (Stevens, 1957). The mathematical presentation of the law is as follows:

$$\psi(I) = kI^{a}$$

I is the magnitude of the stimulus, ψ (I) is the subjective magnitude of the perception, a is a stimulation type dependent exponent, and k is a unit dependent constant. For vibrotactile stimuli, the exponent a ranges from 0,35 to 0,86 and is particularly dependent on stimulus frequency (Gescheider, 1997). It is possible to express the law in seven words: *equal stimulus ratios produce equal subjective ratios* (Stevens, 1957). Weber's law and Stevens' power law have one notable difference. Weber's law assumes a logarithmic function between stimulus and perception while Stevens' power law assumes that the relationship between stimulus and perception follows a power function. Adler, Mayo, & Alon (2014) suggest that the relationship can be either, depending on one biochemical parameter, the effective Hill coefficient.

3.2 PERCEIVING TOUCH: PARALLEL PROCESSES

Many parallel processes occur in touch perception. Besides the somatosensory system, other senses and the stimuli they receive can also influence touch perceptions. In fact, visual or auditory stimuli can produce haptic sensations in the absence of any haptic stimuli (e.g., Lécuyer, 2009; Barratt, & Davis, 2015). To give an often heard example of the mixing between the senses, hearing nails screeching down a chalkboard can induce shivers. Also, on the anatomical level, at least the primary somatosensory cortex and primary auditory cortex are known to have extensive connections (Ro, Ellmore, & Beauchamp, 2012). These connections suggest a cross-talk between the auditory and the somatosensory system.

Inside the somatosensory system, sensations such as vibration, pressure, and tingling also result from the activation of many receptor systems (e.g., Bentley, 1900; Selden, 2004). Further, one perceptual quality of a stimulus can alter another, for instance, humans usually perceive the colder object of otherwise identical objects as heavier (Boff, Kaufman, & Thomas, 1986). Overall, perception is dependent on the integration of information from multiple modalities, which enables accurate estimates of sensory data (Ernst & Bülthoff, 2014).

One high-level parallelism in sensory processing is the division between a faster, automatic, subconscious system and a slower, effortful, conscious system (Kahneman, 2011). In essence, we are not conscious of most of the processing taking place in the somatosensory system. While there is debate over the exact capacities of the conscious and the subconscious system, the subconscious system seems to be vastly superior at information processing. For instance, while the somatosensory system can transfer approximately one million bits per second, we can consciously/psychophysically process this data around five bits per second (Zimmerman, 1989). Thus, for the somatosensory system alone, not to mention all the parallel processing occurring in the other senses, the subconscious processing could occur approximately 200 000 times faster. One proposed analogy for the conscious perception is that of a radar controller monitoring a radar screen (Lehar, 2003). Another analogy is the PC interface, where space-time is the desktop, and physical objects are the icons (Hoffman, Singh, & Prakash, 2015). If we use this analogy, subconscious perception corresponds to all other processing in the computer not visible in the user interface.

Another major parallelism in sensory processing is the interaction between cognition and emotions. As a rule, we cannot understand cognitive processes without understanding affective processes (Ciompi & Panksepp, 2005). Emotions have attractor-like effects, meaning they can capture cognitions into certain patterns of perception, thinking, and action.

Analogous to the perception-decision-action loop, the emotional feedback loop consists of physiological reactions, subjective feelings, and behavioral expression (Gross, 2010). The three core dimensions of the PAD-model of emotions (Mehrabian, 1980) that correspond to these phases are arousal, dominance, and valence. Arousal is strongly correlated with skin conductance, and thus the activity of the sympathetic nervous system (Lang et al., 1993; Bradley, 2000). Dominance, on the other hand, can provide information about a person's feeling of control in a certain context (Bradley & Lang, 1994). Further, valence correlates highly with activity in the facial muscles, and thus emotional expression (Bradley, 2000).

3.3 PERCEIVING TOUCH: TOP-DOWN PROCESSES

While the senses are continuously sampling information, a major contribution to what is perceived is the perceiver's internal presentation of the context, i.e., transference from past learning (Miller, Galanter, & Pribram, 1986; Pribram, 1991; Barsalou, 2008). We can also see this top-down influence on the anatomical level as input from the cerebral cortex controls the neural pathways in the dorsal column (Bear Connors, & Paradiso, 2007). Additionally, top-down attentional mechanisms can influence unconscious information processing (Kiefer, Adams, & Zovko, 2012). The brain fits the information delivered by the skin receptors to a pre-existing neural simulation, a core form of computation in the brain (Barsalou, 2008). Emotions are also an important top-down influence as a contextual interpretation of physiological arousal filters perceptions into categories such as interesting/indifferent or harmless/dangerous, thus affecting subsequent emotional expression and behavior (Posner, Russell, & Peterson, 2005).

Further, the haptic simulation of the body is referred to as a "body matrix" by some researchers (Moseley, Gallace, & Spence, 2012). The researchers propose that a network of multisensory and homeostatic brain areas is responsible for maintaining the subjective body presentation. Demonstrating the flexibility of the body matrix, humans can perceive a stimulus as occurring outside of the body surface (Miyazaki, Hirashima, & Nozaki, 2010; Guterstam, Zeberg, Özçiftci, & Ehrsson, 2016). Body presentation is also plastic in other ways: for instance, a person can be made to feel that an artificial hand (Botvinick & Cohen 1998) or a tail (Steptoe, Steed, & Slater, 2013) belongs to his/her body.

3.4 SUMMARY

In this Chapter, I presented theoretical perspectives into touch perception. I assert that we can understand the nervous system most sensibly in terms of circular causality (Freeman, 2005; Vernon, Lowe, Thill, & Ziemke, 2015) where the separation between cause and effect is ambiguous. Touch perception is an interactive process between bottom-up, parallel, and top-down influences. Previous learning, other senses, conscious and subconscious processing, as well as cognition and emotions, can all influence the resulting touch perception.

In the next Chapter, I will present practically-oriented views into designing vibrotactile cues. I start by phrasing a more detailed definition of vibrotactile cues. Then I will discuss the capabilities of the nervous system in encoding information with different parameters. After this, I will discuss actuation technologies. Finally, I discuss interaction environments for vibrotactile cues.

4 Practical Viewpoints into Designing Vibrotactile Cues

In the previous Chapters, I discussed interaction, technology, and touch from a theoretical perspective. In the current Chapter, I provide more practically oriented viewpoints into the topic, focusing mainly on the vibrotactile submodality. I will begin this Chapter by extending the definition for vibrotactile cues given in the introduction. Furthermore, I will discuss three main factors in the design process for vibrotactile cues: **the perceptual capabilities of the nervous system, the actuator technologies, and the interaction environment**.

4.1 VIBROTACTILE CUES: A DEFINITION

There are some existing definitions for haptic and vibrotactile cues, for instance, as haptic icons (MacLean & Enriquez, 2003), and tactons (Brewster & Brown, 2004). MacLean and Enriquez (2003) defined haptic icons as *computer-generated signals that convey information to a user through force or tactile feedback*. As presented in the introduction, I want to add to this definition by suggesting that there are three primary functions for the cues/icons. First, providing **sensory feedforward** to **assist decision making**. Second, providing **interpretative feedforward** to **assist action**. Third, providing **motor feedback** to **assist perception**. These functions correspond with the perception-decision-action loop described elsewhere (Wickens 2002; van Erp, 2007; Hoffman, Singh, & Prakash, 2015), and the three bottlenecks of information processing (Marois & Ivanoff, 2005). Table 1 describes an overview of the cue types.

All of the cues defined here are assumed to require conscious perception. However, they differ in the phases in which they need it the most: in perception-decision, in decision-action, and in action-perception (Table 1). A fourth possibility is that a vibrotactile cue operates entirely in the subconscious, out of conscious perception (e.g., Riener, Ferscha, Frech, Hackl, & Kaltenberger, 2010). Nonetheless, in this model, the cues are categorized by the phase in which they require the highest level of conscious attention.

	Input	Prompting	Output
Type I cue	Perception	Interpretation in the brain	Decision
Type II cue	Decision	Encoding in the motor system	Action
Type III cue	Action	Decoding in the sensory system	Perception

Table 1. A summary of the cue types

To provide examples of the advantages and disadvantages of the cue types, let us consider a situation where a driver is navigating a route. First, a type I vibrotactile cue refers to feedforward information that mostly affects the loop between perception and decision (Table 1). In other words, the cue notifies a user that some event has taken place in the somatosensory system, causing physiological arousal and encouraging the user to make a decision. The hard limit for bringing two separate events into attention is the attentional blink of 500 ms (Shapiro, Raymond, & Amell, 1997). On the negative side, this type of cue is likely to impair decision-making by encouraging multitasking. Common examples include phone calls and notifications of arriving email and text messages. To give an example of a successful use scenario, a tactile cue could inform a driver of the weather conditions on the road. The driver would have to switch his/her attention to interpreting the cues, but the information would be relevant to the driving task.

Second, a type II vibrotactile cue refers to feedforward information that mostly affects the loop between decision and action (Table 1). In other words, the cue notifies a user that a certain decision should be made, prompting the user to take action or control the situation. Compared to feedforward type I, a type II cue is contextually sensitive. The hard limit for information processing in this phase is the capacity of the short-term memory (Miller, 1956). On the negative side, a cue providing an interpretation can be misinterpreted or give false information, resulting in incorrect actions. For instance, a cue could suggest a driver turn to a dead-end road. On the other hand, a cue could provide invaluable information by signaling that a driver should immediately brake to avoid a collision with another vehicle.

Third, a type III vibrotactile cue refers to feedback information that mostly affects the loop between action and perception (Table 1). In other words, the cue notifies the user of the results of his/her actions, urging the user to perceive the consequences and their emotional valence. The hard limit in this loop for presenting separate feedback is the psychological refractory period of several hundred milliseconds (Welford, 1952). On the negative side, unnecessary or untimely feedback is likely to slow down subsequent responses. For example, if a cue signals that a driver has just exceeded a speed limit, the feedback is already overdue. A timely choice would be to signal the same feedback already as the driver is pressing the gas pedal too heavily, giving more time for adjusting behavior.

4.2 THE CAPABILITIES OF THE NERVOUS SYSTEM

To design vibrotactile cues, we have to understand what kind of information the human nervous system can process effectively. In this Section, I will first discuss different parameters for encoding vibrotactile information. In principle, we have to alter at least one signal parameter to create stimuli with varying information content. The most typical stimulus parameters used to encode vibrotactile cues include frequency, amplitude, waveform, location, duration, and rhythm (e.g., Cheung, van Erp, & Cholewiak, 2008; Jones & Sarter, 2008). It is also possible to communicate emotional information with these parameters (Salminen et al., 2008). In addition to being familiar with the parameters, it is useful to know when to take shortcuts in parameter design. Thus, I will shortly discuss tactile illusions, the role of intuitive knowledge, and the demographics of the user group after discussing the parameters.

Encoding information with spectral parameters

Spectral parameters encode the waveform properties of stimuli. The first spectral parameter we can use with vibrotactile actuators is the shape of the waveform signal, including sine waves, square waves, and sawtooth waves. The sine wave is the most typical wave shape used with vibrotactile actuators, and some actuators are not capable of accurately producing other waveforms (Brown, 2007). A common reason to alter this parameter has been to change the perceived roughness of a stimulus (Brown, Brewster, & Purchase, 2005). Concerning identification rates, Hoggan & Brewster (2007) found a rate of 94 % for waveforms while Enriquez, MacLean, & Chita (2006) reported a rate of 73 %.

The second waveform parameter is frequency, which refers to the number of times a waveform signal repeats per unit of time. Different frequencies produce different sensations. Vibrations below 3 Hz resemble slow kinesthetic motion, 10 to 70 Hz feels like rough or fluttering motion while 100 to 300 Hz is characterized as smooth vibration (Tan, Durlach, Reed, & Rabinowitz, 1999). However, many researchers consider the frequencies of 150-300 Hz, or cycles per second, to be optimal for all body locations (Jones & Sarter, 2008). Furthermore, research suggests that at least a 20-30 % frequency change is required to differentiate between two stimulus levels (Choi & Kuchenbecker, 2013). For the maximum amount of frequency levels, Sherrick (1985) proposes that people could differentiate three to five levels. Concerning identification rates, two studies both reported an identification rate of 81 % for frequency (Enriquez, MacLean, & Chita, 2006; Hoggan & Brewster, 2007).

The third waveform parameter is amplitude, also referred to as magnitude and intensity. This parameter defines the strength of the waveform signal, often measured in volts (electric field) or decibels (sound wave). Concerning amplitude in parameter design, it should be such that the stimulus is above the detection threshold but below the pain threshold (Craig & Sherrick, 1982). Similar to frequency, Geldard (1957) suggests using no more than three levels in practice. Regarding recognition rates, Hoggan & Brewster (2007) reported a recognition rate of 61 percent for amplitude.

A few things make amplitude a complicated parameter for encoding information. First, as amplitude and frequency are intermingled, changing the frequency of a signal also tends to alter the perceived intensity of the stimulus (Geldard, 1957). This alteration has led to the suggestion that designers should vary only one of these parameters (Jones & Sarter, 2008). Second, the relationship between stimulus and perception is not straightforward: doubling the amount of energy in a stimulus does not often mean doubled subjective intensity (Cheung, van Erp, & Cholewiak, 2008). Third, same intensity applied to different spatial locations is perceived differently (Jones & Sarter, 2008).

Encoding information with spatiotemporal parameters

Spatiotemporal parameters encode the space and time dimensions of stimuli. The first spatiotemporal parameter for vibrotactile actuators is spatial location. Concerning specific locations on the body, the fingers, the palm, and the facial area are particularly sensitive to tactile stimulation (Weinstein, 1968). Haptic stimulation and motor response can have high spatial congruency (Aglioti & Tomaiuolo, 2000), suggesting that stimuli are best presented to the body location that is used for the following motor response (De Rosario et al., 2010).

Researchers have concluded that localization of stimuli is affected by the number of the actuators, separation between the actuators, and the anatomical reference point of the actuator location (Cholewiak & Collins, 2003; Cholewiak, Brill, & Schwab, 2004). Another important thing to note with localization is that the location of the actuator is often not the precise location of the stimulus on the skin. A vibrotactile stimulus can travel for many centimeters as circular waves (Cholewiak, Brill, & Schwab, 2004) so it can be impossible to provide the stimulus to a specific location.

Finally, we have the temporal parameters, which further include duration and rhythm. Concerning duration, the skin is sensitive to detecting even brief stimuli. For instance, Kangas et al., (2014) successfully used vibrotactile feedback for gaze gestures with the duration of 20 milliseconds. There is also a practical limit on the other end of the time scale as the potential amount of information transferred per a unit of time decreases with increasing stimulus duration. Geldard (1957) suggested that two seconds would be the limit for practical communication purposes. However, at least in event notifications, people have already perceived durations longer than 200 milliseconds as annoying (Kaaresoja & Linjama, 2005). In terms of recognition, Geldard (1957) suggested that humans could differentiate 25 distinct duration levels in a laboratory setting, but advised using only three levels in practice. Thus, this recommendation corresponds to the number of levels proposed for frequency and amplitude. As a side note, the recognition rates reported for frequency, amplitude, waveform, and duration are from laboratory environments, and the rates would thus likely deteriorate in practical use scenarios.

Concerning rhythm, humans have high discrimination and recognition abilities for tactile rhythms (van Erp and Spapé, 2003; Swerdfeger, Fernquist, Hazelton, & MacLean, 2009), making rhythmic patterns effective for encoding information (Summers, 2000). Humans can distinguish time gaps as short as five milliseconds in successive pulses (Gescheider, Wright, & Verrillo, 2010). This temporal sensitivity is better than that for vision (25 ms) but worse than for hearing (0,01 ms) (Jones & Lederman, 2006). In any case, we can encode relatively large amounts of information with rhythmic on/off pulses. Also, the longer the stimuli, the easier it is to identify differences in a pattern. For instance, researchers have demonstrated this with stimulus durations between 80 and 320 milliseconds (Summers et al., 1997).

For recognition rates, researchers have reported rates of over 90 percent for tactile rhythms (Brown, Brewster, & Purchase, 2005, 2006). Considering perceptual subdimensions, Ternes & MacLean (2008) proposed note length and unevenness as the two characteristics by which tactile rhythms are distinguished. On the other hand, van Erp and Spapé (2003) suggested that tempo and intrusiveness are the two underlying dimensions of tactile melodies.

Finally, compared to the auditory system, designing haptic signals is similar to designing audio signals, except for a few parameters (Nordvall, 2013). One notable difference is that the spatial location of the signal is more important in designing haptics. Another difference is that compared to the auditory system, the skin is rather poor at discriminating differences in waveforms (Summers, 2000; Cholewiak, Brill, & Schwab, 2004). Thus, altering waveform shape, frequency, and amplitude is not the most effective way to encode haptic signals. Instead, varying the spatiotemporal parameters of location, duration, and rhythm seems to be the most promising approach to encoding haptic information (Jones & Sarter, 2008).

Encoding affective information with spectral and spatiotemporal parameters

Arousal, dominance, valence, and emotions such as happiness, sadness, anger, and fear can be effectively communicated by varying haptic stimulus parameters (Salminen et al., 2009; Gatti, Caruso, Bordegoni, & Spence, 2013;

Eid & Al Osman, 2016). Also, most if not all of the parameters that can convey cognitive information can also transfer affective information. For instance, frequency (Lylykangas et al., 2009; Seifi & MacLean, 2013) and amplitude (Raisamo, Raisamo, & Surakka, 2013) have been shown to alter the emotional tone of stimuli. The same holds true for rhythm (Salminen et al., 2009; Seifi & MacLean, 2013), duration (Lylykangas et al., 2009), movement direction (Salminen et al., 2008), and the actuator location (Lylykangas et al., 2009, 2013). I will next describe how previous investigations have connected the different parameters to evaluations of arousal, dominance, and valence.

Concerning frequency and amplitude, studies have reported ascending and descending frequency stimuli to be more arousing (Lylykangas et al., 2009; 2013) and unpleasant (Lylykangas et al., 2013) than constant rate stimuli. Also, Seifi & McLean (2013) found that higher frequency vibrations (175 Hz) were more arousing (i.e., alarming) than lower frequency vibrations (75 Hz). Salminen et al. (2009) demonstrated that higher amplitude stimuli (30 µm) were more arousing and dominant than lower amplitude stimuli (2 µm). Correspondingly, high-intensity air stimuli (50 l/min) have been shown to be more arousing, dominant, and unpleasant than air stimuli with lower (7,5 l/min) flow rate (Tsalamlal, Ouarti, Martin, & Ammi, 2013). Further, Raisamo, Raisamo, & Surakka (2013) showed that dynamic modulation of amplitude was more pleasant and less arousing than discontinuous pulses.

For temporal parameters, longer duration stimuli have been reported to be more pleasant than shorter stimuli (Lylykangas et al., 2009). Salminen et al. (2008) showed that continuous (i.e., shorter bursts) stimuli were judged more arousing and dominant than discontinuous stimuli. Also, stimuli with more bursts have been reported to be more arousing, dominant, and unpleasant than stimuli with fewer bursts (Salminen et al., 2009). Accordingly, Seifi & McLean (2013) showed that stimuli with many short bursts were more alarming and unpleasant than stimuli with fewer bursts. Regarding spatial parameters, stimuli with only forward or backward rotation have been reported to be more pleasant than stimuli with combined forward-backward movement (Salminen et al., 2008). Finally, stimuli in the wrist have been judged more arousing (Lylykangas et al., 2009) and pleasant (Lylykangas et al., 2013) than stimuli in the chest.

Thus, the general trend seems to be that increasing the perceived intensity of stimuli will increase its arousability, dominance, and negative valence. Correspondingly, decreasing the intensity will reduce arousability, and dominance but increase positive valence until the stimuli are below the detection threshold. Also, many stimulus parameters can be altered to achieve an increase in perceived intensity: frequency, amplitude, duration, rhythm or body location. However, as affective communication is contextual (Knapp, Hall, & Horgan, 2013; Eid & Al Osman, 2016), the optimal level of stimulation depends largely on the interaction context.

Taking shortcuts: tactile illusions and intuitive design

Hoffman, Singh, & Prakash (2015) defined perceptual illusions as perceptions that fail to guide adaptive behavior. Perceptual illusions reveal how the perceptual system works in the presence of incomplete, degraded, or ambiguous stimuli (Zavagno, Daneyko, & Actis-Grosso, 2015). These situations may offer valuable insight into how the nervous system processes information, and thus be helpful in designing vibrotactile cues.

One well known example (Lederman & Jones, 2011) is cutaneous saltation, in which three separate actuators create a perception of dynamic movement (Geldard, 1975; Raisamo, Raisamo, & Surakka, 2009; 2013). Instead of feeling distinct pulses, users perceive a smoothly progressing stimulation from the first to the last actuator. Further, cutaneous saltation can be induced to occur outside the body surface (Miyazaki, Hirashima, & Nozaki, 2010). The saltation phenomenon is also robust; people report it as often as when presented an actual tactile stimulus in different locations (Blankenburg, Ruff, Deichmann, Rees, & Driver, 2006).

Another common example is how the properties of an object, such as size (Amazeen & Turvey, 1996) and shape (Kahrimanovic, Tiest, & Kappers, 2010) influence the perceived heaviness of the object. We usually perceive the smaller of two objects of identical weight as heavier. As another example, humans perceive a cube as heavier than a sphere of the same mass.

Tactile illusions can make designing tactile displays easier as we don't necessarily require precise physical parameters to produce a certain perception. Instead, we can use simplified signals, and the nervous system will then fill in the gaps. For instance, Cholwiak and Collins (2000) showed that saltatory stimuli could duplicate sensations generated by higher density tactile arrays. Also, we can use sensory cues from other senses to influence judgments in the haptic system. For example, by adjusting the visual cues accordingly, force feedback devices can simulate seemingly lighter or heavier objects.

Further, in line with the differences in information processing capacity between the conscious and subconscious systems (Zimmerman, 1989), people rely primarily on the subconscious when making decisions and solving problems (Kahneman, 2003). Thus, tapping into the subconscious system can be helpful when designing tactile displays. In a general sense, using the subconscious means making use of innate and previously learned skills and knowledge, also referred to as intuitive knowledge (Naumann et al., 2007). Relying on intuitive knowledge can automate some parts of the three-phased interaction process, thus avoiding bottlenecks in information processing. For instance, Lylykangas et al. (2009, 2013) demonstrated that haptic cues designed for speed regulation conveyed the intended actions in the range of 71-100 percent without previous learning.

Using the subconscious system can also mean that the haptic cues operate entirely without conscious perception, regulating human behavior subliminally (Riener, Chalfoun, & Frasson, 2014). For instance, subliminal notifications with harmonic and disharmonic vibrations can lead to more economical driving behavior (Riener, Ferscha, Frech, Hackl, & Kaltenberger, 2010). Thus, even though a vibrotactile cue is not consciously perceived, it could still influence subsequent behavior.

Moreover, what is intuitive or otherwise suitable for one demographic group may not be so for another. For example, cultures differ in how varied perceptual language they have regarding the sense of touch (San Roque et al., 2015). This observation suggests that people from some cultural backgrounds are more adept at differentiating touch perceptions than people from other backgrounds. Further, the ability to perceive vibrations decreases with age (Verrillo 1979; Wickremaratchi & Llewelyn, 2006). Thus, for instance, the design parameters that are suitable for young university students, a common user group in HTI experiments, may not be effective for the elderly. Finally, gender differences exist in detecting vibrations (Neely & Burström, 2006; Karuei et al., 2011). For example, females seem to be more sensitive to vibrations on the thighs and males to vibrations on the wrists (Karuei et al., 2011).

4.3 ACTUATION TECHNOLOGIES

As mentioned in Chapter 3, the sense of touch includes three anatomical parts, the receptors in the skin, the sensory nervous system, and the brain. Theoretically, we could stimulate any of these parts artificially to generate tactile sensations. For instance, Tabot et al. (2013) stimulated the somatosensory cortex of nonhuman primates to elicit localized percepts on the skin. However, at present, these kinds of invasive approaches have limited applicability outside of specific medical contexts. Non-invasive brain interfaces, on the other hand, are limited to reading the brain signals instead of affecting them (Chatterjee et al., 2007; George, Marchal, Glondu, & Lécuyer, 2012). Thus, at this time stimulating the receptors in the skin seems to be the feasible approach, the approach that we also took in this dissertation.

Stimulating the skin receptors can be done with or without skin contact. Ultrasound (e.g., Carter, Seah, Long, Drinkwater, & Subramanian, 2013; Sand et al., 2015) and air pressure displays (Suzuki, Y., & Kobayashi, 2005) are the most common actuation techniques in the non-contact category (Arafsha, Zhang, Dong, & El Saddik, 2015). Some other non-contact techniques are indirect laser radiation (Lee et al., 2016), and magnetic rendering (Zhang, Dong, & El Saddik, 2016).

Actuation technologies with direct skin contact have been more typical in customer products and research prototypes than non-contact displays. Among these, vibrotactile actuators have been more common than actuators based on static pressure, skin stretch, friction (Choi & Kuchenbecker, 2013), or electrical muscle stimulation (Farbiz, Yu, Manders, & Ahmad, 2007; Lopes, You, Cheng, Marwecki, & Baudisch, 2017). As we used vibrotactile actuators also in our experiments, I will focus the following discussion on them instead of other types of haptic technology.

There are three main categories of vibrotactile actuators: eccentric rotating mass actuators (ERMs), linear resonant actuators (LRAs), and piezoelectric actuators. ERM motors generate vibrations by rotating an asymmetric weight that is attached to a shaft. ERMs are inexpensive but have a relatively poor spatial resolution, and a time lag between the onset of a signal and the actuation of the motor (Kwon, Yang, & Cho, 2010). Further, the frequency and amplitude of stimulation are often coupled, preventing a separate control of the parameters (Jones & Sarter, 2008). Despite the disadvantages, ERMs are common in consumer devices, such as mobile phones and video game controllers. Also, they have been used by some researchers to provide stimulation with mobile phones (e.g., Kaaresoja & Linjama, 2005, Brown & Kaaresoja, 2006). We utilized an ERM actuator in the first experiment of this dissertation.

In LRAs, on the other hand, a coil moves a contact plate up and down, producing vibrations. The major difference between ERMs and LRAs is that LRAs do not have external moving parts. LRAs operate similarly to moving coil loudspeakers, also referred to as voice coil actuators. However, unlike audio speakers, the LRAs are designed to be used within specific frequencies, often in the range of 200-300 Hz. The major advantages of LRAs over ERMs include shorter delay, and more versatile control of stimulus parameters, including duration, frequency, amplitude, and waveform (Choi & Kuchenbecker, 2013). Parameter control includes the possibility to vary frequency and amplitude separately (Jones & Sarter, 2008). In the studies conducted for this thesis, we used LRA actuators in four of the five experiments.

The third common actuator type, a piezoelectric actuator, generates vibrations by moving a plate linearly when applying electricity to it. Compared to ERM and LRA actuators, piezo actuators permit more precise control of stimulus parameters (Tikka & Laitinen, 2006). Also, their advantages include small size and power efficiency (Pasquero et al., 2007). On the other hand, low stimulus intensity and the requirement for high voltages limits piezo actuators (Pasquero et al., 2007). Researchers have used the actuators successfully in touchscreen interaction (e.g., Poupyrev, Maruyama, & Rekimoto, 2002), but the actuators have not been as useful for alarms and notifications that require higher intensity stimuli.

4.4 Interaction environment

The usability of the different parameters and actuation technologies also depends on the interaction environment. With interaction environment, I refer to the outer environment; I discussed the inner environment in Section 4.2. I mostly limit the discussion in this Section to information load in the environment, and the use environments relevant to this thesis. Some significant interaction factors, such as the social environment where the interaction takes place, are not discussed here.

The information load of an environment is an important variable to pay attention. For instance, ambient vibrations in the environment and physical movement can mask signals (Post, Zompa, & Chapman, 1994; Hoggan, Brewster, & Johnston, 2008). Pakkanen et al. (2008) found that low amplitude stimuli perception on the leg while cycling on a stationary bike degraded from around 80 % to under 50 % when participants started cycling. Besides environmental noise (perceptual load) and movement (motor load), the cognitive load of the user can be a highly relevant contextual factor. Compared to the auditory system, response times to haptic signals are less affected by distraction (Mohebbi, Gray, & Tan, 2009), and cognitive load in general (Hanson, Whitaker, & Heron, 2009). Thus, haptic cues are well suited for situations with cognitive overload. On the other hand, the detection of the cues can diminish in the presence of environmental noise.

Currently, vibrotactile displays exist for a rich variety of environments and purposes. The earliest vibrotactile technologies were apparatus that translated speech into touch sensations for hearing impaired people (Gault, 1925, 1927). Users with visual and hearing impairments, in general, have been a significant user group for vibrotactile displays (Kaczmarek and Paul Bach-Y-Rita, 1995). After this initial field of interest, some high-level applications for vibrotactile displays have been navigation and orientation, event notifications, and feedback for actions (Jones & Sarter, 2008). Moreover, haptic displays have been employed in interpersonal communication (Huisman et al., 2013), health care (Kapur et al., 2009), and education (Toennies et al., 2011). From a large perspective, meta-analyses have shown that haptic feedback can improve human performance in many types of environments (Burke et al., 2006; Prewett, Elliott, Walvoord, and Coovert, 2012).

Some applied environments for vibrotactile displays are of particular interest regarding the topic of this dissertation, i.e., movement control. For instance, researchers have employed vibrotactile displays for many purposes in driving. These purposes include providing warning signals (Ho, Reed and Spence, 2006; De Rosario et al., 2010) and navigation cues (van Erp, Van Veen, Jansen, & Dobbins, 2005; van Erp, 2007). Also, they include regulating fuel consumption (Riener, Ferscha, Frech, Hackl, & Kaltenberger, 2010), and speed (Lylykangas et al., 2009, 2013). In this dissertation, **experiments I, II and III** are part of this research area. Second, researchers have also used vibrotactile displays for improving target selection with gaze gestures (Rantala et al., 2015) and in hand-based manipulation (Moehring and Froechlich, 2011). **Experiments IV and V** continue this line of research, focusing on object selection feedback.

4.5 SUMMARY

In this Chapter, I introduced practically-oriented views into designing vibrotactile cues. I began by defining vibrotactile cues. Then I discussed the capabilities of the nervous system in encoding information with different haptic parameters. Then I presented different actuation technologies for tactile feedback. Finally, I discussed the role of interaction environment for vibrotactile cues.

The perceptual capabilities of the nervous system, the actuator technologies, and the interaction environment together form the interaction context, previously defined as *any information that can be used to characterize the situation of an entity*. Research into just noticeable differences vividly demonstrates the importance of context for even simple stimulus detection. Some sources report JNDs of 5 % to 15 % for haptic stimuli (Jones, 1989; Jones and Hunter, 1992). On the other hand, Bicchi, Scilingo, & De Rossi, 2000 recite a JND of 46 % for a haptic display. Still, other researchers report a JND of 100 % for haptic force feedback (Allin, Matsuoka and Klatzky, 2002). Thus, it is essential to understand as many aspects of the interaction context as possible to design effective haptic cues.

In the next Chapter, I introduce the five experiments conducted for this thesis. I will first provide a summary of the experiments and then proceed to discuss them individually.

5 Introducing the Experiments

The primary goal of the experiments was to investigate means to assist navigation and object selection in human-technology interaction with short, intuitive vibrotactile cues. We studied feedback (type III) and interpretative feedforward (type II) cues (Table 1) in the leg, head and hand areas of the body, utilizing cues of varying length, from 20 to 500 milliseconds. For actuation, we used linear resonant actuators in four experiments (II-V) and an ERM motor in experiment I.

We conducted five experiments in four application areas: pedestrian navigation, car navigation, object selection by head movement, and hand-based object selection. In experiment I, we compared a novel haptic navigation technique to tactile icons in pedestrian navigation. In experiments II and III, we examined how directional navigation cues in two body locations, the thighs, and the temples, affect driving in a lane change task. In experiment IV, we investigated if vibrotactile cues on the temples could improve head turn based left-right interaction in an object selection task. Finally, in the fifth experiment, we examined the suitability of two locations for presenting hands-free object selection feedback in VR, the temples, and the wrist. Table 2 summarizes the main parameters of the cues used in the experiments.

	Cue type	Location	Duration	Actuator type	Application area
Experiment I	II & III	Hand	500 ms	ERM motor	Pedestrian navigation
Experiment II	II	Thighs	120 ms	Voice coil	Car navigation
Experiment III	II	Thighs and temples	80 ms	Voice coil & linear motor	Car navigation
Experiment IV	III	Temples	20 ms	Linear motor	Object selection by head movement
Experiment V	III	Wrist and temples	30 ms	Linear motor	Object selection by hand movement

Table 2. A summary of the cue parameters used in the experiments

I will next introduce the experiments, starting with their aims and methods. Further, I will present the main results and consider their implications briefly. The purpose of this Chapter is to is to provide an overview of each experiment. In the next Chapter, I will discuss the findings on a more general level.

5.1 Experiment 1: Orientation inquiry: a new haptic interaction technique for non-visual pedestrian navigation

Reference

Raisamo, R., Nukarinen, T., Pystynen, J., Mäkinen, E., & Kildal, J. (2012). Orientation inquiry: a new haptic interaction technique for non-visual pedestrian navigation. In *EuroHaptics 2012, International Conference on Human Haptic Sensing and Touch Enabled Computer Applications* (pp. 139-144). Springer, Berlin, Heidelberg.

Objectives and Methods

The main motivation behind the first experiment was that visual distraction impairs attention and is a notable cause of traffic accidents (Madden and Rainie, 2010). Also, previous studies (e.g., van Erp, Van Veen, Jansen, & Dobbins, 2005) have shown that vibrotactile cues are effective for presenting navigation information, and could perhaps support visual displays. Thus, we decided to investigate a new interaction technique to reduce visual distraction and cognitive load in pedestrian navigation situations.

In experiment I, we compared a novel orientation inquiry technique to simple tactile icons (Figure 2). In orientation inquiry, the user initiated an interaction by tilting the phone in the expected navigation direction and received a 500 ms vibration feedback if the direction was correct. In tactile icons, the system initiated the interaction automatically, and the user's task was then to interpret and execute the feedforward instructions, which were learned before the trials.

In the experiment, six participants navigated two simulated routes in a laboratory environment using the techniques. For both techniques, we measured subjective preference, navigation errors and the number of times the user's repeated the instructions before a decision.

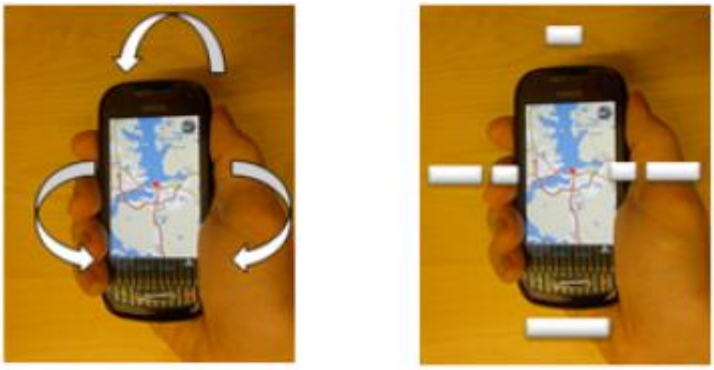

Figure 2. Visualizing the orientation inquiry technique (left) and the tactile cues (right)

Results and Discussion

The results showed that the participants, on average, made fewer errors (0 vs 0,67) and repeats (0,3 vs 0,47) with the orientation technique. Also, the participants gave more positive ratings to the inquiry method than to the tactile icons. Among other attributes, the participants described the orientation inquiry as simpler (+3 vs. +0,7), clearer (+3,2 vs. +1), and easier (+2.7 vs. +0.7) than the icons.

The experiment provides preliminary evidence that user-initiated feedback cues (orientation inquiry) may perform better than computer-initiated feedforward cues (tactile icons) in pedestrian navigation. Thus, in this context, the decrease in sensory-cognitive load could outweigh the increased motor demands for overall performance.

5.2 Experiment 2: Effects of directional haptic and non-speech audio cues in a cognitively demanding navigation task

Reference

Nukarinen, T., Raisamo, R., Farooq, A., Evreinov, G., & Surakka, V. (2014). Effects of directional haptic and non-speech audio cues in a cognitively demanding navigation task. In *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational* (pp. 61-64). ACM.

Objectives and Methods

Along with reducing the visual-cognitive load in navigation, a more specific aim for experiment II was to study how directional vibrotactile cues compare to other cue modalities in car navigation. Previous research indicated that directional haptic cues could orientate visual spatial attention

(Tan, Gray, Young, & Taylor, 2003). Thus, we compared 120 ms directional haptic cues actuated by a driving seat to three other cues: non-speech audio-, simultaneous haptic-audio-, and visual text cues.

In the experiment, sixteen participants drove a Lane Change Test simulator (Figure 3) with the different cues. The task of the participants was to recognize the feedforward cue (left or right) by responding as fast as possible using a tablet and then changing the lane accordingly. To increase cognitive load, the participants also did a backward counting task during the experiment. We measured reaction times and error rates for the different conditions. Further, we asked the subjective preferences of the participants, and they filled up NASA-TLX questionnaires for each condition.

Figure 3. The experimental setup for experiments II and III

Results and Discussion

The results showed that in comparison to visual text cues, all the other cues led to significantly faster reactions. The average reaction times were 603 milliseconds faster for the haptic than the visual cues. The haptic condition was the most preferred as 37 percent of the participants preferred the cues. Moreover, the participants evaluated the haptic cues as the least physically demanding. However, the participants made significantly more errors with haptic (5,1 % of the turns) than audio (0,7 %) or haptic-audio (2,2 %) cues. While not statistically significant, the visual condition (2,6 %) also had less errors than the haptic condition. Also, the experiment demonstrated that there was little difference between audio, haptic and haptic-audio cues regarding reaction times.

The results indicate that vibrotactile cues can improve reaction times in cogntiively demanding driving conditions. On the other hand, vibrotactile cues can also lead to more navigation errors than audio cues. For instance, cognitive distraction or ambient vibrations in the driving environment could diminish the usability of the vibrotactile cues. For practical purposes, other interaction modalities could support the cues in navigation tasks.

5.3 Experiment 3: Delivering directional haptic cues through eyeglasses and a seat

Reference

Nukarinen, T., Rantala, J., Farooq, A., & Raisamo, R. (2015). Delivering directional haptic cues through eyeglasses and a seat. In *World Haptics Conference (WHC), 2015 IEEE* (pp. 345-350). IEEE.

Objectives and Methods

The motivation for experiment III was largely the same as for experiments I and II: reducing visual distraction and cognitive load in navigation. Additionally, we compared two actuator locations in experiment III, the driving seat and haptic eyeglasses (see Figure 4). The aim was to explore how the two types of directional haptic cues compare to each other and visual text cues.

Twelve participants drove the Lane Change Test simulator with visual text cues, 80 ms haptic cues actuated by the car seat (Figure 3) and haptic cues of the same length actuated by the eyeglasses (Figure 4). We asked the participants to confirm the recognition of a directional cue (left or right) by pressing an arrow on a tablet screen and by navigating to the corresponding lane. The participants also did the same backward counting task as in experiment II. Similar to experiment II, the measurements included reaction times, error rates, the NASA-TLX questionnaire, and free-form answers for subjective preferences.

Figure 4. The haptic glasses (left) and the actuator used in the glasses (right) in experiments III and IV

Results and Discussion

The results showed that in comparison to the visual text cues, the haptic cues were reacted to significantly faster. The average reaction times were

390 milliseconds faster for the seat and 470 milliseconds faster for the glasses. The participants also evaluated haptic cueing as less frustrating than visual cueing. The haptic eyeglasses fared slightly, although not significantly, better than the haptic seat in the evaluations. The differences in navigation errors were not statistically significant, but the participants made more errors with the haptic cues on the thighs (4,2 %) and the temples (2,6 %) than with the visual cues (1 %). Further, the experiment showed that 83 percent of the participants preferred the haptic cues, and out of those 70 percent preferred the eyeglasses while 30 percent preferred the seat.

The results demonstrate that haptic glasses can be a suitable approach to presenting navigation cues, perhaps better than a driving seat. Otherwise, the results are in agreement with those in experiment II; haptic feedforward cues lead to faster reactions but also to more errors. Thus, the cues could be supported by other modalities for practical navigation scenarios.

5.4 Experiment 4: Evaluation of HeadTurn: An Interaction Technique Using the Gaze and Head Turns

Reference

Nukarinen, T., Kangas, J., Špakov, O., Isokoski, P., Akkil, D., Rantala, J., & Raisamo, R. (2016). Evaluation of HeadTurn: An Interaction Technique Using the Gaze and Head Turns. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (article 43). ACM.

Objectives and Methods

In experiment IV, we developed an interaction technique that utilizes head turns and eye movements for selecting objects in the environment. Visual feedback from eye movements is naturally poor in comparison to manual user interfaces, and thus a promising target for vibrotactile cues. Our aim was to investigate if adding haptic feedback to visual feedback could improve the head turn interaction. As we had experienced success with the haptic eyeglasses in the third experiment, it seemed worthwhile to adapt this particular location for presenting the vibrotactile cues.

In the experiment, participants used the technique to select targets on a PC screen. The task was to adjust a number to a given value with left-right head turns using three different intervals between the numbers, 217 ms, 290 ms, and 435 ms. The vibrotactile cues were then used to enhance the interaction by providing feedback from the users' head turns. We compared visual+haptic feedback conditions with the three intervals to three visual-only feedback conditions. In the haptic condition, a 20-millisecond vibration given through a vibrating eyeglass frame accompanied each number change (Figure 4).

Results and Discussion

The results did not show statistically significant differences in task completion times between the different number changing intervals. However, task completion times with haptic feedback were slightly faster for all of the three intervals. 92 percent of the participants interpreted the haptic feedback favorably, describing the feedback as helpful, useful, functional or appropriate for the task in some way. We also received a few negative comments about the vibrotactile cues concerning mainly the amount of stimulation and delayed feedback in the higher number changing speeds.

The results suggest that vibrotactile feedback can be a helpful addition for interaction techniques utilizing eye and head movements. However, specific attention must be paid to the timeliness and strength of the feedback to avoid delays and annoyance from excess stimulation.

5.5 Experiment 5: Hands-free Vibrotactile Feedback for Object Selection Tasks in Virtual Reality

Reference

Nukarinen, T., Kangas, J., Rantala, J., Pakkanen, T. & Raisamo, R. (2018). Hands-free Vibrotactile Feedback for Object Selection Tasks in Virtual Reality. *In Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology* (p. 94). ACM.

Objectives and Methods

The motivation for experiment V was to explore vibrotactile object picking feedback for two body locations that do not require a hand controller. For example, industrial applications of VR may require that the user's hands are free for specific tasks. Based on the previous experiments and other related research (e.g., Lee & Starner, 2010; de Jesus Oliveira, Brayda, Nedel, & Maciel, 2017), we chose the wrist and the temples as the locations to investigate (Figure 5).

We evaluated vibrotactile collision feedback in the wrist, and the temples for proximal, hand-based object picking. We studied if 30 ms vibrotactile cues would affect user preferences or interaction speed in a virtual reality grasping task. We compared visual feedback to three visual-haptic conditions, providing haptic feedback on the participants' wrists, temples or simultaneously on both locations.

Figure 5. Two actuators were on the headset against the participant's temples (left), and one actuator was on the wristband of the controller holding hand (right)

Results and Discussion

The results showed that 94 percent of the participants preferred haptic feedback over visual-only feedback. Further, the wrist feedback was the most preferred method among the haptic conditions, chosen by 63 % of the participants. The participants rated the wrist feedback as significantly more pleasant, arousing, and effective than the temple feedback, in addition to feeling more control. Task completion times were not affected by the feedback, and the participants generally felt that the task was easy.

The results indicate that the wrist is a more promising feedback location than the temples for continuous, hand-based object selection in a low cognitive load environment. Also, the additional benefit of multi-location feedback appears to be minimal. Finally, the results suggest that a feedback location that is suboptimal for a task may still be a better choice than no haptic feedback at all.

6 Discussion

In the experiments conducted for this thesis, we investigated the use of vibrotactile cues for assisting navigation and object selection in human-technology interaction. Beyond the individual studies, the aim was also to arrive at higher level principles for improving movement control. As the experiments fit into two larger domains, navigation and object selection, I will first discuss these domains individually. Finally, I will discuss the findings from the experiments I-V together.

The main motivation behind the experiments I, II, and III was the *mismatch between visually demanding technology and traffic.* Visual distraction and impaired attention are one of the most notable causes of traffic accidents (Madden and Rainie, 2010). Enhancing visual interaction with touch interaction could increase traffic safety, but the vibrotactile submodality also poses a challenge. Users may fail to notice vibration cues due to their mental state, motor activity or the conditions of the environment (Post, Zompa, & Chapman, 1994; Hoggan, Brewster, & Johnston, 2008).

One solution to this problem is to use user-initiated vibrotactile cues. Instead of expecting the user to stay vigilant for possible alerts, the user could actively inquire navigation directions when needed. Active touch generally has higher perceptual performance than passive touch (Lederman & Klatzky, 1987), and the idea that this may also apply to vibrotactile cues was tried out in experiment I.

Motor vehicle navigation requires a different solution than the one investigated in the first experiment. One reason for this is that the driving task already occupies the hands, which makes the smartphone approach impractical. Thus, we wanted to investigate other possible locations and chose the thighs and the temples as the locations. Further, while we thought that it is not plausible to use the orientation inquiry technique as in experiment I, tactile icons (i.e., Brewster, & Brown, 2004) could also induce unnecessary cognitive load on the driver. Dismissing this alternative, we arrived at directional cueing. Directional cues could intuitively guide the driver's attention in a certain direction without the cognitive interpretation involved with tactile icons.

Three general findings emerged from the experiments I, II, and III. First, on-demand navigation cueing seems preferential to computer-initiated cueing in pedestrian navigation, and it may be best to keep the abstractions as simple as possible. This finding comes from the experiment I where we compared the orientation inquiry and tactile icons. We reason that even simple abstractions can increase the cognitive load of the user. Further, in practical use, computer-initiated cueing can cause constant demands on the user's attention, which could increase information load more than user-initiated cueing.

Second, if we use feedforward navigation cues, it may be best to support the cues with other modalities. The experiments II and III demonstrated that the attentional cueing approach (Tan, Gray, Young, & Taylor, 2003) is indeed plausible for car navigation. Directionally cueing left or right can automatically guide the user's attention to the desired direction. However, both experiments also showed that feedforward cueing sometimes led to missed cues, perhaps due to distractions or habituation. For instance, ambient vibrations in the environment or the user's movements could mask cue signals. This finding suggests that precise navigation requires complementary modalities to support the vibrotactile feedforward, such as a visual display. That vibrotactile navigation cues alone are not an effective replacement for visual alerts is also supported by a previous meta-analysis (Prewett, Elliott, Walvoord, & Coovert, 2012).

Third, the temple area, in particular, seems to be a feasible location for navigation cues. In experiment III, the glasses performed slightly better than the seat in most measurements, and 70 % of the participants preferred the glasses over the seat. Also, haptic glasses would allow seamless integration between car navigation and pedestrian navigation while keeping the user's hands available for other tasks. We reason that the temples could be a practical cue location for improving movement control in other environments as well.

The navigation experiments had some contextual constraints that may limit the applicability of these findings. First, navigating in space includes more than just linear left-right-forward-backward turns. This simplification limits the application of the results to more complex navigation environments. Second, the experiments were done in a laboratory environment that lacked many of the distractions which burden the user's mind in traffic. We tried to compensate for this with the counting task in experiments II and III, but actual contexts of use could pose challenges that we could not take into account.

As in experiments I, II, and III, the main motivation behind the experiments IV and V was the *mismatch between visually demanding technology and humans*. Visual emphasis is inherent in eye tracking and virtual reality applications, which were the areas of investigation in experiments IV and V. On the other hand, it is common that these systems pay little attention to the haptic part of the interaction. If haptic cueing exists at all, it often occupies the hands, such as a vibrating hand controller in VR systems.

One solution to alleviating the visual demand would be hands-free haptic feedback not restricted to any particular controller device. As the haptic eyeglasses were a relative success in the third experiment, we chose to specifically investigate the temple area for presenting the vibrotactile cues in experiments IV and V. We also included the wrist area as an alternative location in experiment V.

We arrived at two general findings after conducting the two experiments. First, the preference for vibrotactile feedback was high among the participants in both experiments. All but one participant preferred to have the vibrotactile feedback in the tasks in both experiments. Also, this preference was not related to task performance as the participants were not significantly faster with haptics than without haptics. Earlier research has also demonstrated strong preferences for tactile feedback even without large improvements in task performance (e.g., Tähkäpää & Raisamo, 2002; Brewster, Chohan, & Brown, 2007). One possible explanation is that vibrotactile feedback increases the sense of control in the task. There were some implications for this in experiment V as the participants reported more control with the wrist and combined feedback than with the less potent temple feedback.

Second, the usability of the temple area for vibrotactile cueing depends on many factors. While experiments III and IV had promising results regarding temple feedback, the results were somewhat disappointing in experiment V. Three factors, in particular, could explain the results. First as haptic stimulation and motor response can have high spatial congruency (Aglioti & Tomaiuolo, 2000), feedback is perhaps best presented to the body location used for the following motor response (De Rosario et al., 2010). Accordingly, temple feedback could be more suitable for VR applications that utilize attentional cueing or gaze-based control, offering congruency with the body location. Second, the actuation wearable was different in experiment V, a VR headset, as the two previous experiments used eyeglasses instead. We experienced some technical difficulties with the head-mounted actuators. Thus, the actuation device could have a large impact on the results. Third, the experiments also imply that vibrotactile feedback may be more compatible for slower than faster-paced tasks. There is a limit to the appropriate amount of vibrotactile feedback in the temple area. In experiments IV and V, we received a few negative comments about the excessive amount of stimulation on the head area. Temple area may not be a convenient choice for continuous vibrotactile feedback, and instead function better for infrequent cues.

The experiments IV and V had a limitation that concerns the context of the research. In both experiments, other cognitive and motor demands on the users were low during the task. Thus, the results are mainly applicable to environments where the user is not distracted by his/her movement or by other tasks. However, according to Wickens' multiple resource theory (Wickens, 2002, 2008), environments with higher cognitive load could make the vibrotactile cues even more useful performance-wise.

Both navigation and object selection are tasks of movement control. In each experiment, the users performed goal-oriented tasks where vibrotactile cues were used to assist the movement control. Further, in both task types, the visual sense was heavily loaded by the task. The focus in the navigation experiments II and III was on feedforward or computer-initiated cues. On the other hand, the object selection cues in experiments IV and V had their focus on feedback or user-initiated cues. Experiment I compared both types of cues, bringing the domains together.

Regarding the experiments as a whole, the main finding is that vibrotactile feedback cues seem to be preferential to feedforward cues in movement control. In experiments IV and V with feedback, 92-96 percent of the participants preferred to have the vibrotactile feedback in the tasks. The numbers are larger than the ones in experiments II and III where the preferences varied between 56-83 percent for the vibrotactile feedforward. In these feedforward experiments, the participants who chose visual cues described them as easier and less demanding. Experiments II and III did not include a visual-tactile condition, which could partly explain the lower preferences for vibrotactile cues than in experiments IV and V. However, in experiment I that included both types of cues, feedback, and feedforward, the feedback cues received more positive ratings in spite of requiring extra hand movements.

Additionally, the performance gains from the cues do not seem to be related to cue preference. The feedback in experiments IV and V did not improve task completion times, but this did not affect preferences negatively. On the other hand, while the vibrotactile and audio feedforward cues in experiments II and III improved reaction times, 17-25 percent of the participants still preferred visual cues.

Moreover, we intentionally increased cognitive demand in experiments II and III. On the other hand, experiments IV and V were less demanding for the participants. Wickens' multiple resource theory (Wickens, 2002, 2008) predicts that a high cognitive load environment is required to see performance differences between visual and visual-tactile conditions. Our results conform to this prediction with reaction times and interaction speed. However, the cue type, feedback or feedforward, seems more important for the subjective preference of the cues.

The finding raises the question that why would feedback be preferred to feedforward as a general rule. From a psychological perspective, a possible reason is that feedforward prompts users to react to technology while in feedback the technology reacts to the users' behavior. With feedback, users may feel that they are controlling the situation. With feedforward, users may feel that the situation is controlling them. For instance, according to self-determination theory of human motivation (Ryan & Deci, 2000), competence, autonomy, and relatedness are the three intrinsic human motivators. Perhaps the needs for autonomy and competence are more fulfilled with feedback than feedforward cues.

Another, more information-oriented perspective on the issue is that feedforward may contribute more to information overload than feedback as feedback could save resources in the perception and decision stages of interaction. Previous research has shown that users can extract more information from the environment with active rather than passive touch (Lederman & Klatzky, 1987). Active touch, with feedback cueing in this case, could also conserve sensory-cognitive resources. With feedforward, the user has to stay attentive to perceive incoming cues to avoid missing relevant information. This constant monitoring requires perceptual resources. Also, type 1 feedforward cues (Table 1) could further distract the user's current task if s/he focuses on a different task at the moment. This sudden demand to focus on a novel task, such as decoding a cue, demands cognitive resources. With feedback, the user expects to receive a cue for the current task after an action, so there is no need for constant monitoring (feedforward types I and II) or sudden contextual switching (feedforward type I).

Limitations and Further Research

To be able to develop more rigorous research in the future, it is crucial to understand the limitations of the current work. First, we conducted all of the experiments in a laboratory setting. Actual use contexts can introduce unpredictable variables into the interaction, which may completely change the current predictions. Thus, it is essential to replicate the results in non-artificial contexts of use.

Second, all of the study participants were university students or employees. Thus, we can mainly apply the findings to a young-middle-aged demographic group that has better than average understanding of interactive technology. Future studies could include other age groups and less technology acquainted people to improve the generalizability of the results.

Third, we did not systematically measure the three types of information load (attention, memory, speed) in the experiments. We measured error rates (experiments 1, 2, 3, and 4), speed (2, 3, 4, and 5), or both (2, 3, and 4). However, we can still divide errors into errors of attention and errors of memory: did the user miss or forget/misinterpret the cue. The prevailing research methodologies do not seem to enable this separation. While the author is not aware of any objective measurements that make this distinction, researchers could develop questionnaires for assessing these two types of errors.

Fourth, the studies did not vary the cue types systematically. The reason is that the idea of three cue types arose from the data of the current experiments. Future investigators could vary the cue types in controlled experiments to study their effects on attention, memory, and processing speed.

Based on the results and their interpretations, we can set forward four hypotheses for further research in movement control. First, feedforward type I cues are subjectively less preferred than feedforward type II or feedback cues. Second, feedforward type II cues are subjectively less preferred than feedback cues, but more preferred than feedforward I cues. Third, feedforward type I cues cause more information load than feedforward type II or feedback cues. Fourth, feedforward type II cues cause less information load than feedforward I cues but more than feedback cues.

Navigation is one application where to test these hypotheses. For instance, let us consider a situation where a driver navigates with visual-haptic cues. He has three options at an intersection, turning left, turning right or going forward. First, a feedforward I cue could automatically notify the driver of an approaching intersection with a single vibrotactile pulse. The driver has to check the visual display after feeling the cue to see the proper direction. Second, a feedforward II cue could automatically notify the driver by a pulse either in the temples or the forehead. The cue does not require the driver to switch from the driving task to a visual display checking task. Third, the driver could receive the spatially located cue as feedback by raising his/her eyebrows. Thus, the driver could decide if a navigation cue is necessary for a certain environment and also choose the specific time to receive the cue.

For a new user, the feedback approach could require more cognitive resources and result in more mistakes than the feedforward cues. However, feedback cues lack the constant distraction caused by unnecessary feedforward that may contribute to information overload. Additionally, it is plausible that voluntary feedback leads to better internalization than feedforward in the longer term as it requires the users to take responsibility for their decisions. In the longer timescale, the cues could become obsolete as the person would learn the navigation routes.

7 Conclusions

In this dissertation, I investigated how to assist navigation and object selection with vibrotactile cues in human-technology interaction. The thesis included five experiments, in which the primary goal was to explore ways to reduce information load. The following three points summarize the conclusions that we can draw from the experiments:

- If the context of movement control allows the use of both feedback and feedforward cues, feedback cues are a reasonable choice as the first option. In this dissertation, vibrotactile feedback cues seemed to be preferential to feedforward cues when considering all of the collected data. Feedback cueing, compared to feedforward cueing, could conserve perceptual and cognitive resources.

- When designing vibrotactile feedforward cues, using low-level abstractions, such as directional cues, and supporting the interaction with other modalities, can keep the information load as low as possible. Also, other modalities should complement the cues as some feedforward cues are likely to be missed no matter their design.

- The temple area is a feasible actuation location for vibrotactile cues in movement control, including navigation cues and object selection cues with head turns. However, the area may not be as good for other types of tasks, such as hand-based object selection. Further, temple cues may be better suited for tasks that require infrequent vibrotactile feedback rather than faster-paced tasks.

Specifically, these conclusions can inform further research and practical applications of vibrotactile displays in the field of human-technology interaction. The results also have wider implications. Technology that uses feedforward cueing on a large scale, such as smartphone notifications, comes with a price. Among other things, constant feedforward seems to be turning us into reactive multitaskers with short attention spans. Replacing feedforward with feedback cueing wherever possible could reduce information load and bring back some control from technology to us humans in our personal lives. In the longer term, this kind of change could have significant benefits for our well-being on the societal level.

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Paper I

Raisamo, R., Nukarinen, T., Pystynen, J., Mäkinen, E., & Kildal, J. (2012). Orientation inquiry: a new haptic interaction technique for non-visual pedestrian navigation. In *EuroHaptics 2012, International Conference on Human Haptic Sensing and Touch Enabled Computer Applications* (pp. 139-144). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-31404-9_24

Orientation Inquiry: A New Haptic Interaction Technique for Non-visual Pedestrian Navigation

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Abstract. Current mobile navigation systems often require visual attention. This may lead to both inconvenient and unsafe use while walking. In this paper, we are introducing orientation inquiry, a new haptic interaction technique for non-visual pedestrian navigation. In a pilot experiment, the orientation inquiry technique was compared to tactile icons used as vibration patterns indicating the direction of travel. The results suggest that both techniques are suitable for navigation, but the participants preferred orientation inquiry to tactile icons.

Keywords: Orientation inquiry, Pedestrian navigation, Tactile feedback, Wayfinding.

1 Introduction

Navigation using maps currently requires heavy use of the user's eyes: the user needs to look at the map repeatedly during navigation. This heavy use of vision creates problems for any user, such as safety issues and cognitive overload. It may be dangerous to walk along the streets while looking at the map when cars that are circulating around, or other pedestrians are coming from around the corner. For some users, such as persons who are blind or visually impaired, map-based navigation techniques are not usable at all. This group of users needs more than any other the help of location information for navigation.

The current solutions for non-visual navigation present two problems:

(a) They require special hardware, such as belts, arrays of vibrotactile actuators, or 3D audio equipment.
(b) They overload the user cognitively with audio and/or haptic signals, which are relevant only sometimes, but need to be attended to all the time.

Jacob et al. [7] listed four reasons to integrate haptics into navigation: freeing the eyes for other purposes, avoiding language barriers with global audiences, enabling faster decision-making, and reducing cognitive load. In a system by Ertan et al. [1], the user

P. Isokoski and J. Springare (Eds.): EuroHaptics 2012, Part II, LNCS 7283, pp. 139–144, 2012.

was wearing a vest and a backpack. The system has been followed by many belt-like implementations [2,3,5]. The disadvantages of these prototypes are that they are not available to the wider audience and they require the user to carry an extra device.

In the last few years, some haptic navigation aids have been developed for mobile phones. Lin et al. [4] introduced tactile icons for pedestrian navigation. Tactile icons are vibration patterns used to encode travel direction. Earlier work on tactile icons, such as Tactons [10, 12] and Haptic Icons [11] has shown that high recognition rates can be achieved with a small amount of training.

Pielot et al. [6] presented PocketNavigator, a vibrotactile navigation system for Android phones. PocketNavigator's key feature was continuous vibration feedback used as a tactile compass. NaviRadar [8] took further this kind of approach by introducing the ability to communicate directions in full 360° range. Only one tactile pattern was used. Even though many research prototypes exist, no tactile navigation solution has become widely used by consumers. There is still room for innovation.

This paper is organized as follows: First, we introduce the orientation inquiry and the use of tactile icons implemented as comparison. This is followed by description of the pilot experiment. The paper is concluded with a discussion and a summary.

2 Orientation Inquiry

A key feature of the *orientation inquiry* interaction technique is to provide tactile feedback on intersections. First, five short vibration bursts are given to get the user's attention when approaching an intersection. When using the orientation inquiry the user can actively inquire the right direction by tilting the phone to the expected direction and by getting vibration feedback to verify the correct direction (see Fig. 1a). The user is the one initiating the additional guidance only when it is needed, while in earlier solutions the guidance was initiated by the system.

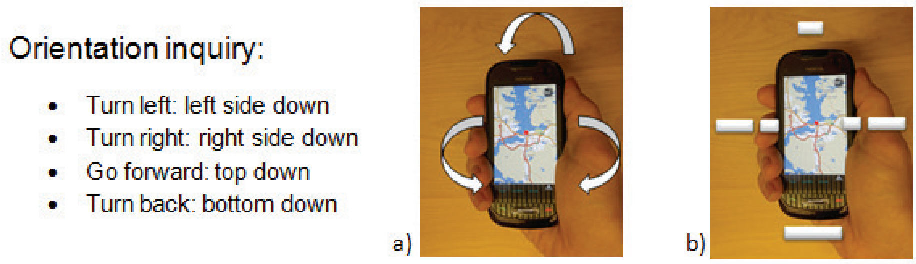
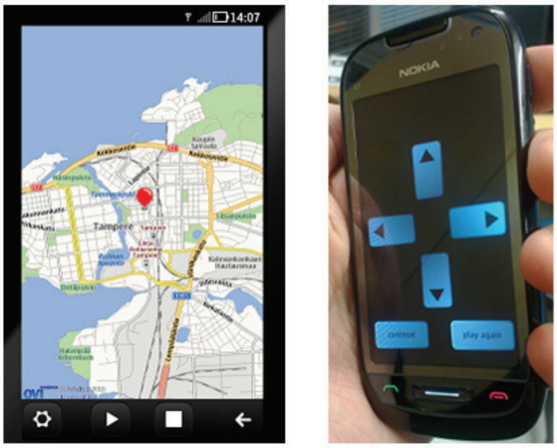


Fig. 1. (a) Orientation inquiry technique (b) Visualization of tactile icons

When using orientation inquiry, the user rotates the phone to different directions and the phone vibrates when it is rotated to the direction where the user should go. Vibration feedback (a 500 ms pulse) is given when the phone is rotated to the direction where the user should go. For example, if the user should turn left, when the user rotates the phone to the left, vibrotactile feedback is given. A rotation of 30° degrees is required to start the vibration. In measuring rotations, the initial orientation of the mobile device is first determined and the rotation is measured in relation to this initial orientation. If the device is determined to be upside down, the coordinate system is reversed in calculating the directions. This makes the technique more robust independent of the actual orientation of the device in the user's hand.

2.1 Proof of Concept Application for Pilot Evaluation

The orientation inquiry technique was initially implemented for Nokia phones running Symbian^3 OS (such as Nokia C7-00). In addition, the application works on any Symbian Anna and Belle phones. It was programmed with the Qt framework using Nokia Maps. In Fig. 2a there is a snapshot of the route display. Fig 2b shows the selection screen used by the test participants to enter the direction to walk in the simulated laboratory test. It is not directly related to the non-visual interaction technique.



a) b)

Fig. 2. (a) Main view of the application (b) Testing device and testing application

For comparison purposes, the direction information can be presented in two ways in the testing application, via orientation inquiry (Fig. 1a) and via tactile icons (Fig. 1b). In this context, tactile icons are vibration patterns that are used to suggest where the user should go: left, right, forwards or backwards. A short burst (100 ms) followed by a 100 ms break and by a longer burst (400 ms), indicates that the user should turn right. Turning left is presented with a 300 ms burst followed by a 100 ms break and by a 200 ms burst. A short burst (250 ms) means going forward and a long one (1000 ms) implies need to turn back. Tactile icons were designed to be as simple as distinguishable from each other as possible.

When the application is launched, the user's position is shown on the map (see Fig. 2a). The destination can then be entered via the keyboard. After that the navigation can be started. In both techniques, vibration feedback is utilized for two purposes: to get the user's attention when approaching an intersection and to direct the user to the correct direction. Both tactile icons and orientation inquiry are utilized to express four directions: left, right, forward and backward.

3 Pilot Experiment

We carried out a pilot experiment in a laboratory setting where user navigated along simulated routes. The goal of the experiment was to evaluate the feasibility of the system. We were also interested in comparing the preciseness and pleasantness of the tactile icons and orientation inquiry. The navigation relied solely on haptics as headphones were used to prevent vibration sounds and no visual feedback was given.

3.1 Procedure

Six participants, 3 female and 3 male, took part in the pilot experiment. All participants were right-handed but one preferred left hand when using a phone. Before the actual experiment a pilot test with two participants was done.

At first, participants were given general instructions and a short training session for the first interaction method. After that the actual navigation was carried out and then a short questionnaire was answered. When the task was finished, the procedure was repeated with the other method, excluding the general instructions part. After the tasks, a questionnaire was answered. A nine point scale was used to assess the techniques (from -4 to 4). The different assessments can be seen in Fig. 3.

The actual tests had two similar routes for both methods: one with 13 and the other with 15 turns. Half of the participants navigated first via tactile icons while the other half started with orientation inquiry. The routes were also counterbalanced. Participants could replay the tactile icons and repeat orientation inquiry in an intersection as many times as they wished. Directional arrow button was pressed to choose the direction and a continue button was pressed to confirm the choice and carry on.

3.2 Results

The preciseness of different methods was evaluated and compared to each other. All participants managed to navigate using orientation inquiry without errors. One participant made four errors with tactile icons. In addition, the repeat count with tactile icons and orientation inquiry was compared. Participants made more repeats per turn with tactile icons than with orientation inquiry (0.47 vs. 0.30 on average).

Assessing the techniques separately, navigation with orientation inquiry was described as simpler (+3 vs. +0.7), easier (+3.2 vs. +1) and clearer (+2.7 vs. +0.7). Participants also thought that orientation inquiry was better (+2.2 vs. +1.3), more successful (+3.3 vs. +2.5), more creative (+3 vs. +2.2), more pleasant (+1.7 vs. +1) and more practical (+1.7 vs. +1.5). Fig. 3 illustrates the differences. However, Wilcoxon's signed rank test revealed that only the difference in the easiness of use was statistically significant ($W = 0$, $p < 0.05$), largely due to the small number of users in this pilot experiment.

The end-of-session questionnaires showed that five of the six participants found orientation inquiry more pleasant than tactile icons. Most participants commented that orientation inquiry was easier to remember and did not cause the same cognitive load as tactile icons. Orientation inquiry was seen as sufficient without visual feedback (4 of 6 participants). Participants also commented that both techniques would be useful when visual feedback is not available. Only one of the participants said that she could not imagine using either technique for navigation.

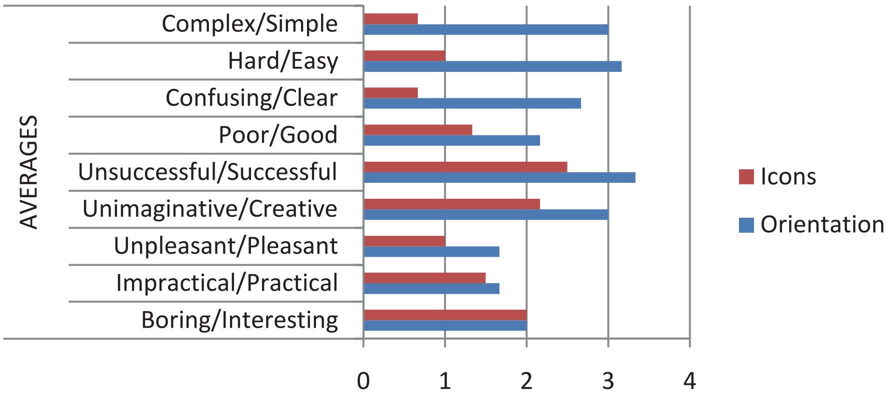


Fig. 3. Comparison of the techniques. A longer bar means more positive feedback.

4 Discussion and Summary

Orientation inquiry technique may be used with any mobile device that contains one haptic actuator and a sensor to measure the orientation of the device. The idea can be utilized with a portable device (handheld, worn on body, eye-wear) or built in a car.

Our approach is the most similar to work by Lin et al. [4] as tactile icons are used to provide turn-by-turn feedback for the user. The major difference is that orientation inquiry utilizes an accelerometer found in many mobile phones. Another difference is that our method does not provide constant feedback: it is only given in intersections when requested by the user. Continuous feedback has been associated with increased cognitive workload [9], which can be avoided with the orientation inquiry technique. Another benefit from not using continuous feedback is saving energy which leads to improved battery performance.

In this paper, we presented orientation inquiry, a haptic interaction technique designed for pedestrian use. Tactile feedback was utilized to help the user navigate to a destination even when visual feedback is not available or it cannot be used. We proposed a novel technique: orientation inquiry. Results from a pilot experiment were promising as orientation inquiry was clearly preferred to tactile icons by the participants. This paper presented a proof of concept for the new haptic interaction technique. Further research with more participants is needed to further confirm the positive effects observed the pilot experiment.

Acknowledgments. This research was funded by the Finnish Funding Agency for Technology and Innovation (Tekes), decision numbers 40159/09 and 40289/11. For more information, visit http://hapimm.cs.uta.fi/ and http://hapticauto.sis.uta.fi.

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Paper II

Nukarinen, T., Raisamo, R., Farooq, A., Evreinov, G., & Surakka, V. (2014). Effects of directional haptic and non-speech audio cues in a cognitively demanding navigation task. In *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational* (pp. 61-64). ACM. https://doi.org/10.1145/2639189.2639231

Effects of Directional Haptic and Non-Speech Audio Cues in a Cognitively Demanding Navigation Task

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ABSTRACT
Existing car navigation systems require visual or auditory attention. Providing the driver with directional cues could potentially increase safety. We conducted an experiment comparing directional haptic and non-speech audio cues to visual cueing in a navigation task. Participants (N=16) drove the Lane Change Test simulator with different navigational cues. The participants were to recognize the directional cue (left or right) by responding as fast as possible using a tablet. Reaction times and errors were measured. The participants were also interviewed about the different cues and filled up the NASA-TLX questionnaire. The results showed that in comparison to visual cues all the other cues were reacted to significantly faster. Haptic only cueing resulted in the most errors, but it was evaluated as the most pleasant and the least physically demanding. The results suggest that non-visual cueing could improve safety.

Author Keywords
Car navigation; directional cues; tactile displays; haptic stimuli

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): User Interfaces – *Haptic I/O, Auditory (non-speech) feedback.*

INTRODUCTION
Car navigation systems are widely used nowadays. These systems generally rely on giving visual and auditory instructions. This can have some disadvantages for the driver because they recruit senses and attentional resources that are central for the driving task itself. Visual in-vehicle navigation information displays have been shown to have negative effects on traffic safety (e.g. [7, 10]). A major problem is visual distraction caused by gazing at the navigator. Processing the symbols on 2D maps requires some cognitive effort. Auditory channel on the other hand suffers from noisy environments (e.g. music and conversations), which can reduce its usability as the only modality. Tactile feedback is seldom used in car navigation and it could bypass some of the limitations that visual-audio systems have. Jacob et al. [6] listed four reasons to integrate haptics into mobile navigation. The reasons are: freeing the eyes for other purposes, enabling faster decision-making, reducing cognitive load and avoiding language barriers with global audiences. They also apply in car navigation context.

So how can the importance of visual channel be reduced in navigation situations? Navigation cues should be intuitive to minimize cognitive load, but previous studies have given mixed results on the subject [15]. Many studies in haptic navigation have been focused on tactile icons, such as Tactons [5] and Haptic Icons [11]. Although these studies show that high recognition rates can be achieved with tactile icons, these icons still cause higher cognitive load. They take time to interpret and require learning. One reason for this might be that the tactile stimulations use one channel to provide messages. So splitting this single channel information in two channels could facilitate cognitive processing in certain situations like navigating to the left and right. Thus, directional cues in the present context are defined as audio or tactile stimuli given to one side of the body to alert of an event occurring on the same side. Simple directional cues could direct attention like a tap on the shoulder without increasing cognitive requirements in already demanding situations [15].

Attentional cueing using haptics has been shown to decrease reaction times [14] compared to visual cues. In another study [9] using audio cues, conflicting message semantics and sound-source location led to an increased error rate. This resembles the dominant approach in current navigation systems as all messages come from the same direction. For example, a navigator on the right side of the driver may instruct him to turn left. To prevent any extra cognitive load the use of simple directional cues (left and right) could be beneficial. As these cues cannot provide the

NordiCHI '14, October 26 - 30 2014, Helsinki, Finland
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http://dx.doi.org/10.1145/2639189.2639231

same amount of information as more complex tactile icons could, they could be combined with conventional visual cues.

Current car navigation research has focused mainly on three forms of tactile displays: tactile seats (e.g. [4]), tactile belts (e.g. [1]) and tactile steering wheels (e.g. [8]). We chose the seat approach: stimuli were provided on the driver's thighs. Using the seat has several advantages: stimulus can be precisely located in one side of the body; the stimulus device can also be an integral part of the car and have constant contact with the driver. Communicating complex messages without direct contact with the skin could be challenging but simple directional cues should be more easily recognizable. In a previous study with a tactile seat recognition rates of over 90 % have been achieved [4].

Directionally congruent haptic and audio cues can increase performance [14, 9] but the results dealing with display modality and cognitive load are mixed [15]. One study [8] found that speech-based audio-haptic cues reduced driver distraction compared to single modality cues. They also reported that haptic cues decreased performance compared to audio cues. Another study [1] found that haptic cues did not increase performance compared to a conventional car navigation system.

We applied two kinds of directional cues: haptic cues on the driver's thighs and audio cues provided by headphones. Our goal was to have easily distinguishable cues that could reduce driver distraction in a cognitively demanding driving situation. To our knowledge, directional haptic-audio cues have not been studied together with visual cues before. Our research question was the following: are directional audio, haptic, or haptic-audio cues less distractive than visual cues and what is the preferred modality for the users in a cognitively demanding driving situation?

METHOD

Participants

Sixteen participants (14 male, 2 female, mean age 35, range 18-52 years) took part in the experiment. All were right-handed and had a normal vision, hearing and sense of touch by their own report. All had a driving license and drove 1000-35000 kilometers per year (in average 14000).

Apparatus

We built a haptic seat prototype for the experiment. This prototype consisted of a car seat with integrated actuators to provide haptic cues. In addition, we used a desktop PC, gaming steering wheel and pedals for the driving task and a tablet for the navigation. Headphones were used to provide audio cues. We acknowledge that this does not correspond to a real driving environment [8]. We chose headphones to make audio and haptic cues more comparable: reducing the effect of background noise and distance to the body. The whole setup is shown in Figure 1a. We used the Lane Change Test simulator [12] and a self-implemented navigation task software with data logging.

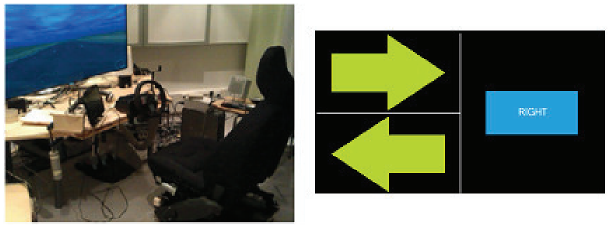

Figure 1. (a) Experimental setup. (b) Tablet screen prompting a choice after a (visual) cue.

Stimuli

Cues were used to express two directions: left and right. Separate attentional cues were not used as the actual cues were designed to both capture attention and to guide the driver. Baseline visual condition consisted of blue boxes (11,5 x 5,5 cm) indicating the direction (left or right) in white letters. They were presented in the center of the right side of the screen without time limit (Figure 1b). We did not use arrows as they were employed as choice buttons (Figure 1b) and that would have provided an advantage for the visual cues. Directional audio condition provided audio cues for the navigation task via headphones with sine wave (time of stimulation 120 ms) sounds to left or right ear. Directional haptics condition utilized cues of the same length (120 ms) provided by the haptic seat prototype, a sine wave type vibration on the driver's left or right thigh indicating a turn. For audio signal frequency and time period were 2050 Hz and 490 ms, for vibration 12.5 Hz and 80 ms. Design guidelines [2] suggest that duration of a signal burst should be between 100-150 ms. Synchronicity of the cues was verified in internal tests; testers reported that the cues were experienced simultaneously. In every condition, participants had to choose the direction by pressing arrow buttons on the tablet screen (Figure 1b). The arrows were arranged vertically so that it would be practical to reverse their positions, thus standardizing button location between trials. Had they been arranged horizontally, right-left condition would have been clearly non-congruent.

Experimental Design

Three tasks were performed simultaneously in the study: driving a Lane Change Test simulator, counting numbers and performing a navigation task. We wanted to have multiple measures of cognitive load to see if cues have different effects on these measures. We compared a visual navigation condition (baseline) to three other conditions: directional audio, directional haptics and directional haptics-audio; the within-subjects independent variable was display modality. As objective dependent variables we measured reaction time to the navigation messages, error rate in navigation, lane deviation (mean distance from the ideal driving line), driving errors (choosing the wrong lane), and the amount of numbers counted (with counting errors subtracted). The participants filled in NASA-TLX questionnaires [3] for each stimulus condition. The participants were also shortly interviewed after the tests. Cognitive load was increased by asking the participants to count numbers, which has been shown to significantly affect reaction times in a driving task [13]. Wickens' [16] multiple resource theory predicts that high cognitive load and multiple tasks are needed to observe performance differences between conditions.

Procedure

The study was conducted in a laboratory where participants were driving the Lane Change Test simulator. This consisted of driving a straight road and performing lane changes to left or right according to the instructions given by the simulator. Six different tracks were driven, one with each display modality and also one for practice and another one after the modality conditions to rule out learning effects. There were 18 lane changes (9 lefts, 9 rights) in each track. Time between lane changes was around nine seconds. Participants were also doing the counting task which consisted of counting forward seven numbers at a time (7, 14, 21…). In addition, participants had a navigation task in the experimental conditions, choosing between left and right arrows on the tablet screen based on the stimulus received. This happened every 6-10 seconds, 17 times (8-9 lefts, 8-9 rights) in total. Half of the participants had the arrow positions reversed. Each participant completed every route but the display modality order was counterbalanced.

In the beginning the participants were briefly familiarized with the experiment and they had a chance to practice recognizing the cues and driving with the counting task. They were also allowed to adjust headphones to a comfortable volume and seat distance to the steering wheel and pedals. The actual driving tasks for the four modality conditions were then carried out. Reaction times, navigation errors and mean lane deviation were measured. Counting errors and numbers counted correctly were also measured during the tasks. After each task, a NASA-TLX questionnaire was answered. An interview of the different methods was made after the experiment. Each condition lasted for 5-10 minutes, the experiment in total 45 minutes.

RESULTS

Interviews and NASA-TLX

Participants were asked to name the most pleasant stimulus method and tell why they chose it (see Figure 2). In addition, participants were asked if they would use directional audio or directional haptic cues for navigation and why. Six participants (37 %) preferred the haptic-only method. It was described as clear (4 participants), comfortable (2 participants) and less distractive than the other methods (2 participants). Two participants said that it felt unpleasant and another two said that visual cues would support haptic cues. Four participants (25 %) preferred the visual method. Visual cues were described as easier (2) and as less demanding than the other methods (2). Haptic-audio and audio methods were both preferred by three participants (19 %). Haptic-audio method was especially liked for its multimodality (3) which was said to be helpful. Audio cues were described as clear (3) but it was also said that other sources of noise in the traffic disturb them (3). Five participants said that visual cues would support audio cues.

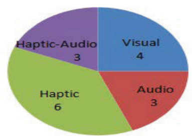

Figure 2. The most pleasant navigation method.

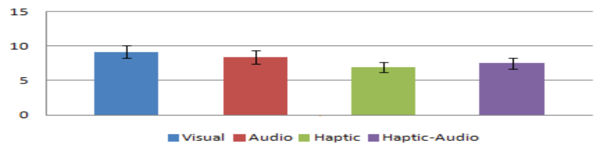

Figure 3. Physical demand in NASA-TLX.

NASA-TLX questionnaire data was analyzed using Friedman tests. We found a statistically significant difference in physical demand ($p < 0.041$). Other items were not statistically significant. Pairwise comparisons for physical demand were made with Wilcoxon tests. We found a statistically significant difference between conditions: haptic condition was less demanding than visual ($p < 0.022$) or audio ($p < 0.027$) condition (Figure 3).

Reaction times and navigation errors

The reaction times in the navigation task were analyzed using one-way repeated measures ANOVA and Bonferroni-corrected post-hoc pairwise comparisons. ANOVA revealed statistically significant differences between conditions ($p < 0.001$). The results showed that participants reacted 465-603 ms faster in haptic ($p < 0.001$), haptic-audio ($p < 0.001$) and audio ($p < 0.002$) conditions compared to the visual condition (Figure 4). Navigation errors were analyzed using Friedman tests. A statistically significant difference between conditions was found ($p < 0.011$). After this pairwise comparisons were made with Wilcoxon tests. Total amount of errors was fairly low in all conditions (0.7-5.1% of turns), but there were significantly more navigation errors in haptic than in audio ($p < 0.012$) or haptic-audio ($p < 0.033$) conditions (Figure 5). There were no statistically significant differences in lane deviations, numbers counted correctly, or in driving errors.

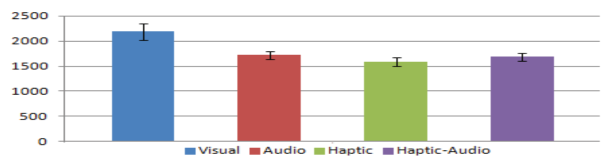

Figure 4. Reaction times in the navigation task.

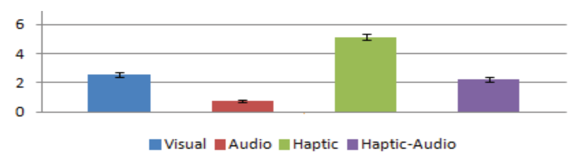

Figure 5. Error percentages in the navigation task.

DISCUSSION AND CONCLUSIONS

We presented an experiment which shows that haptic, audio and haptic-audio cues were processed faster than visual cues. This may indicate a lower cognitive demand when using haptic, audio and haptic-audio directional cues. Multimodal cues (haptic-audio) did not lead to faster processing than unimodal cues (haptic or audio). This suggests that using haptic and audio cues together might not give extra benefits in performance.

Haptic cues required less physical effort than visual or audio cues but led to significantly more errors than audio and haptic-audio cues. These results may reflect driver characteristics and the driving environment, as people have different sensitivities to touch and sound and respond differently to stressful situations, which may lead to missing cues. Directional cues were widely preferred subjectively: 75 % of participants preferred haptic-, audio- or haptic-audio cues to visual cues. In addition, 94 % of participants would use directional haptic or audio cues alone or combined to other modalities.

Some issues should be considered when interpreting the results. Headphones are not a feasible option for a real car context. In addition, navigating the environment includes more than just left-right turns. Generalizing the results should be therefore done with caution. Acknowledging these limitations, the findings support the idea of using directional cueing in navigation. Directional cues could be used to increase driving safety in situations that are demanding on the visual and auditory senses. There are some design implications to existing navigation devices; tactile, audio and visual cues could be located on the same side as the turns are. It is likely that directional cueing would function well for other purposes than just navigation (e.g., collision warning or notification of a blind area). More research is needed to see how directional cues would function in a real car context.

ACNOWLEDGMENTS

This research was funded by the Finnish Funding Agency for Technology and Innovation (Tekes), decision number 40289/11. More information: http://hapticauto.sis.uta.fi.

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Paper III

Nukarinen, T., Rantala, J., Farooq, A., & Raisamo, R. (2015). Delivering directional haptic cues through eyeglasses and a seat. In *World Haptics Conference (WHC), 2015 IEEE* (pp. 345-350). https://doi.org/10.1109/WHC.2015.7177736

Delivering Directional Haptic Cues through Eyeglasses and a Seat*

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***Abstract*—Navigation systems usually require visual or auditory attention. Providing the user with haptic cues could potentially decrease cognitive demand in navigation. This study is investigating the use of haptic eyeglasses in navigation. We conducted an experiment comparing directional haptic cues to visual cueing in a car navigation task. Participants (N=12) drove the Lane Change Test simulator with visual text cues, haptic cues given by the eyeglasses and haptic cues given by a car seat. The participants were asked to confirm the recognition of a directional cue (left or right) by pressing an arrow on a tablet screen and by navigating to the corresponding lane. Reaction times and errors were measured. The participants filled in the NASA-TLX questionnaire and were also interviewed about the different cues. The results showed that in comparison to the visual text cues the haptic cues were reacted to significantly faster. Haptic cueing was also evaluated as less frustrating than visual cueing. The haptic eyeglasses fared slightly, although not significantly, better than the haptic seat in subjective and objective evaluations. The paper suggests that haptic eyeglasses can decrease cognitive demand in navigation and have many possible applications.**

I. INTRODUCTION

Navigation aids are widely utilized nowadays in many different contexts, for instance, in driving, cycling and walking. These navigation systems usually provide visual and auditory instructions. This can be detrimental for the user because the devices burden senses and attentional resources that are essential for behaving safely in traffic. Visual in-vehicle navigation information displays have been shown to negatively affect traffic safety [1, 2, 3]. Visual distraction caused by gazing at the navigator is a problem and processing 2D maps and their symbols also requires some cognitive effort. Auditory channel also has a disadvantage because noisy environments (e.g. traffic, music, conversations) can hinder its usability. Tactile channel on the other hand is rarely used in navigation and could evade some of the limitations that visual-audio systems have. Haptics work in noisy surroundings and free the eyes for more important purposes.

What are effective ways to use haptics in navigation systems? This is the question we are trying to answer with our research. Navigation cues should be designed to be intuitive to minimize cognitive load, but previous studies have often not succeed in this effort [4]. Intuitiveness in this study is defined as stimuli automatically triggering the required response, therefore minimizing the need for directed attention. Studies in haptic navigation have often been focused on tactile icons, such as Tactons [5] and Haptic Icons [6]. While these studies show that recognition rates can be high with tactile icons, the icons still cause significant cognitive load. This means that some conscious processing happens between the stimuli and the response: the icons take time to interpret and require learning. One reason for the need of conscious processing might be that the tactile stimulations use one channel to provide messages. Splitting this single channel information in two or more channels could facilitate cognitive processing in certain situations like navigating. For instance, different directions can be displayed with different channels (e.g. left, right), corresponding to those directions. Thus, we define directional navigation cues in the present context as tactile stimuli given to one side of the body to alert of an incoming turn to the same side. Attention can be directed with simple directional cues like a tap on the shoulder while not increasing cognitive requirements of already demanding situations [4].

A study [7] using audio cues showed that conflicting message semantics and sound-source location led to an increased error rate. This resembles the most common approach in current navigation systems as all navigation cues come from the same direction. For instance, a navigator on the right side of a driver may instruct him to turn left. The use of simple directional cues (left and right) could be beneficial to reduce the cognitive requirements of using a navigator. As the information provided by these cues is quite simple, they could be combined with visual cues in real applications. Directionally congruent audio and haptic cues have been shown to increase performance [7, 8]. However, one study [9] found that compared to audio cues, haptic cues decreased performance. Another study [1] reported that haptic cues had similar performance as a conventional car navigation system. An earlier study [10] showed that while haptic cues were generally liked and resulted in faster performance than visual text cues, they also resulted in more errors than audio cues. The results concerning haptic navigation cues seem to be quite mixed and a highly effective solution is yet to be found.

The present study will focus on car navigation. Current car navigation research has mainly concentrated on three types of tactile displays: tactile seats [10, 11, 12, 13], tactile belts [14, 15, 16] and tactile steering wheels [9, 17, 18]. An earlier work [10] used a haptic seat: cues were provided on the driver's thighs. Using the seat had some advantages because cues could be accurately located on one side of the body. In addition the stimulus device could be integrated in the seat and have constant contact with the driver. A success rate of 94.9 % was achieved in the previous study's [10] navigation task with the haptic seat.

*Research was funded by the Academy of Finland, project Haptic Gaze Interaction, decision number 260026. More information: www.uta.fi/sis/tauchi/projects/hagi.html.

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The study [10] brought up some issues concerning the haptic seat. First, the cues can be confused with other sources of vibration (e.g. mobile phone, rough road). Clothing and seat texture between the skin and the haptic actuators also alters the vibrations. Second, some people perceived the cues as unpleasant. One solution would be to make the vibrations less potent. However, this would further hinder the ability to detect the cues because of environmental noise. Therefore, we decided to try a novel approach for this study.

We are proposing a new type of tactile navigation display: the haptic eyeglasses. Although helmet-mounted tactile displays have been studied for military applications [19], the head area has not been studied before in the context of car navigation. This area should be less prone to vibrations in the environment (e.g. mobile phone) and the eyeglasses can also have direct contact with the skin unlike with the seat. In addition, this allows us to use less powerful vibrations which might help with the issue of unpleasantness. The haptic eyeglasses can also provide cues accurately to one side of the body and have constant skin contact with the driver. The eyeglasses cannot be an integral part of the car but this can also be seen as an advantage: for instance, they could also be used in pedestrian navigation.

We compared two kinds of directional haptic cues to visual text cues in this study. The text cues appeared on the left field of vision, haptic cues on the driver's temporal area of the head (the eyeglasses) and the driver's thighs (the seat). The goal was to have cues that are comfortable and reduce cognitive demand in driving. Our research question was: are directional cues given by haptic eyeglasses and a haptic seat less distractive than visual cues and what is the preferred modality for the users in a navigation situation?

II. METHOD

A. Participants

Twelve university students (8 male, 4 female, mean age 23, range 19-38 years) took part in the experiment. 11 of 12 the participants were right-handed. All had a normal or corrected vision and a normal sense of touch by their own report. None of the participants wore eyeglasses (for vision correction) in the test. All of them had a driving license and they drove 2300 kilometers a year on average (range 0-7500 kilometers).

B. Apparatus

The haptic eyeglasses were one of the two ways to provide haptic cues. The eyeglasses designed originally for use with gaze gestures [20] were based on a sunglass frame with lenses removed. Three vibrotactile actuators (LVM8, Matsushita Electric Industrial Co., Japan, Figure 1c) were attached to the frames so that two of them were mounted on the tips of the temples and one on top of the bridge (see Figure 1a). The total weight of the eyeglasses was 23 grams. The actuators were chosen mainly due to their small diameter of 0.8 cm that allowed easy placement to the frames. The placement of the actuators was guided by the fact that the frontal and temporal regions of the head are sensitive to vibration [19] and also natural contact points when wearing eyeglasses. The actuators were attached firmly to the eyeglasses so that the resulting vibration was felt mostly via the frames and not only through direct skin contact with the actuators. An earlier study indicated that users wearing the eyeglasses could distinguish between stimulation from the left, front and right actuators with an average accuracy of 85-100% [20].

The haptic seat was the second way to provide the haptic cues (see Figure 1b). It was also part of the previous experiment to study directional cues [10]. This prototype provided haptic stimulation with integrated actuators located under the driver's thighs. The prototype utilized two Hiwave HIAX25C10-8/HS voice coil actuators (Figure 1d, one for each leg), embedded into the lower part of the driver's seat. To increase the stimulation area, the voice coil actuators were fitted with a horizontal plastic extension of 15.2 cm in length. The HiWave actuators were powered by a PWM amplifier and a signal generator. For the purpose of this experiment the signal generator was set to provide a sinusoidal wave at 170 Hz with a PK-PK(Peak to Peak) amplitude value of 18.8V where the signal stimulation time was fixed at 80ms (barring residual vibrations). The same apparatus was used to actuate the transducers attached to the eyeglasses. Hence the signal frequency, amplitude and time period were kept constant for both devices, because this ensured that the stimulation frequency was within the resonance frequencies of both actuators.

To describe the rest of the setup, it contained a desktop PC, a television, a gaming steering wheel and pedals for the driving task and a tablet for the navigation task. The tablet was located on the left side of the steering wheel at arm's distance. The setup also contained a windshield to make the driving experience more immersive. The whole setup is shown in Figure 2a. Lane Change Test simulator [21] was utilized for the driving task in the study but not for analyzing purposes. To present the navigation cues and to log reaction times we used self-implemented software as in a previous study [10].

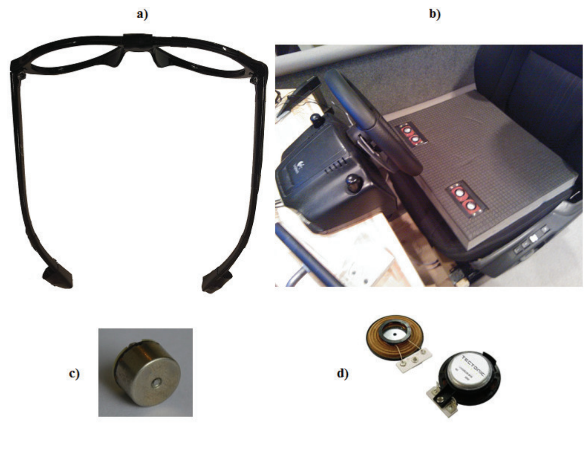

Figure 1. (a) The haptic eyeglasses. (b) The haptic seat with the cushion removed. (c) The actuator used in the eyeglasses. (d) The actuators in the seat.

a)

b)

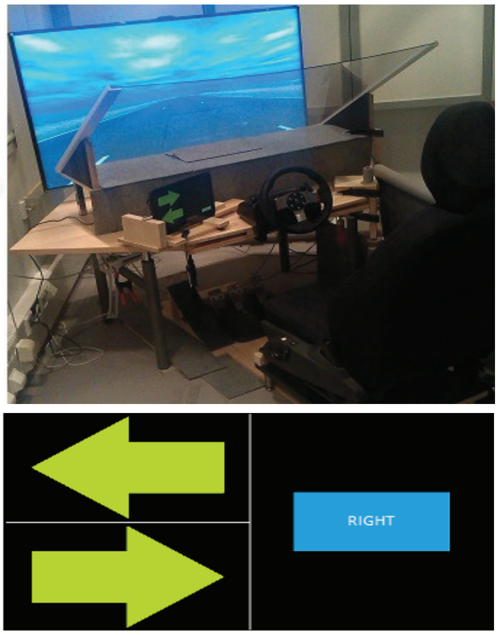

Figure 2. (a) The experiment setup. (b) The tablet screen prompting a choice after a (visual text) cue.

C. Stimuli

Cues were used to signal two directions: left and right. We designed the cues to both capture attention and to guide the driver to the right lane. Visual condition consisted of blue boxes (11.5 x 5.5 cm) on the tablet screen, which indicated the direction (left or right) in white letters. These cues were shown in the center of the right side of the screen with no time limit (Figure 2). We did not want to use arrows as they were utilized as choice buttons (Figure 2) and that would have given an advantage for the visual cues.

The haptic eyeglasses provided directional cues in the navigation task with 80 ms vibrations to the left or right temporal area of the head. The haptic seat prototype utilized identical cues (80 ms), a vibration given on the participants' left or right thigh indicating a turn. Design guidelines [22] suggest that signal burst duration should be between 100-150 ms. In addition, it has been suggested [19] that when stimulating the head with vibration signal frequency should not exceed 150 Hz to be comfortable. However, our internal tests showed that 80 ms and 170 Hz was easily noticeable and comfortable enough for this purpose, while also having less resonating sounds than some other combinations. Additionally, in our testing we employed miniature unidirectional piezoelectric sensors (Bestar FT-20T-6) to measure the vertical components of the vibration signals delivered to the point of contact for both the haptic seat and the eyeglasses. These were found to be 6.3 V and 760 mV respectively, illustrating that the medium of signal propagation played a considerable role in shaping the delivered stimulation [23]. However, we believe that the integration of the applied signal did not affect the user's ability to perceive the stimulus itself in any way.

In each condition, participants chose the direction by pressing arrow buttons on the tablet's screen. The arrows were arranged vertically making it practical to reverse their positions, thus standardizing button location between each trial. If they had been arranged horizontally, right-left condition would have been non-congruent in half of the trials.

C. Experimental Design

Three tasks were carried out simultaneously in the experiment: driving the Lane Change Test simulator [21], counting numbers and performing a navigation task. Visual text cues (baseline condition) were compared to two haptic conditions: directional cues with the eyeglasses and the seat; the within-subjects independent variable was cue modality. As objective dependent variables we measured reaction time to the navigation cues, error rate in navigation and the number count.

Reaction time was the main objective measure indicating processing efficiency. Navigation errors included congruent and non-congruent errors. Congruent errors were errors where the participant both selected a wrong button from the tablet and then a wrong lane in the LCT. In non-congruent errors the participant chose the correct button or the lane but made an error in the other task. Cognitive demand was increased by asking the participants to count numbers as it has been shown that counting significantly affects reaction times in a driving task [24]. Wickens' [25, 26] multiple resource theory predicts that high cognitive load and multiple tasks are needed to observe performance differences in the tasks.

As a subjective dependent variable we used the NASA-TLX questionnaire [27]. NASA-TLX is a workload rating procedure with six subscales (range 1-20): mental demand, physical demand, temporal demand, own performance, effort and frustration. The participants were also shortly interviewed after the tests. We asked the participants to name the most pleasant cue and tell why they chose it (see Figure 3a). Participants were also inquired if they would use directional haptic cues given by eyeglasses or seat for navigation and why.

C. Procedure

The study was carried out in a laboratory where participants were driving the Lane Change Test simulator. Driving the simulator only included driving a three-lane straight road and did not include following the LCT road signs. Four different tracks were driven, one with each condition and also one for practice. Participants were also counting numbers which consisted of counting forward seven numbers at a time (7, 14, 21…). Finally, participants had the navigation task in the experimental conditions, choosing between left and right arrows on the tablet screen based on the cues received. After this they had to turn to the lane indicated by the cue and then come back to the center lane. This happened every 6-10 seconds, 16 times (8 lefts, 8 rights) in total. Arrow position was reversed for half of the participants. Display modality order and left-right sequences were also counterbalanced.

Before the experiment participants filled in a short background form. After this they were familiarized with the study and they could practice sensing the cues and driving with the counting task. Participants were also allowed to adjust seat distance to the steering wheel and pedals.

Participants were told to imagine the arrows on the tablet as turn signals they had to press before turning to the lane hinted by the cue and then come back to the middle lane. The driving tasks for the three conditions were then carried out. Reaction times and navigation errors were measured during the tasks as well as counting errors and numbers counted. NASA-TLX questionnaire was filled after each driving task. After the experiment, an interview of the different methods was conducted. The experiment in total lasted around 30 minutes, 5-10 minutes for each condition.

III. RESULTS

A. Interviews

Seven participants (58 %) preferred haptic cues with the eyeglasses (Figure 3a). The cues were described as clear (3 participants) and as easy to perceive (4 participants). Three participants also said that the cues allow their eyes and attention to stay on the road. There were also mentions that the eyeglasses are not practical (5) and that they are uncomfortable to wear (4 participants). Three people said that head might be a better location than legs for the cues. Overall, 58 % of the participants said they could imagine using the cues for navigation.

Cues with the haptic seat were preferred the most by three participants (25 %, Figure 3a). The participants described the cues as easy (4), effective (2), and said that they allow your eyes and attention to stay on the road (3). Negative aspects were also mentioned; three people said you can miss the cues and two participants also felt them as distractive. All in all, 75 % of the participants said they could imagine using the cues for navigation.

Two people (17 %) liked the visual cues the most (Figure 3a). The most common mention (8 participants) was that visual cues should be used together with haptic cues. The reason the participants wanted visual cues was that the driver could verify the right direction at least in some occasions if the haptic cues are missed. Visual cues alone were generally not liked: six people mentioned they make driving harder in some ways when you have to concentrate on the navigator.

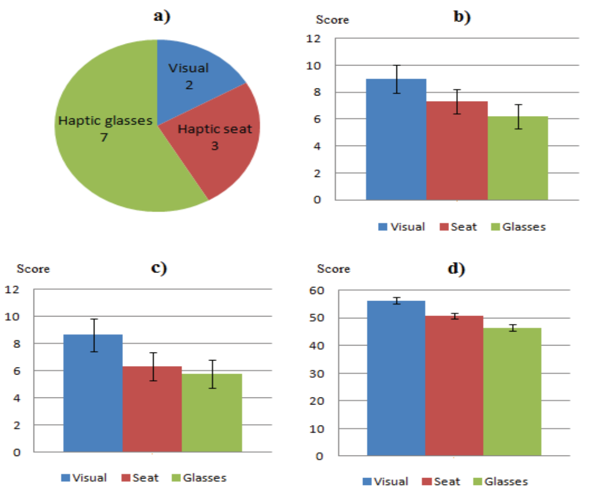

Figure 3. (a) The most pleasant navigation method. (b) Frustration. (c) Physical demand. (d) NASA-TLX total score.

B. NASA-TLX

Friedman tests were used to analyze NASA-TLX questionnaire data. We found a statistically significant difference in frustration (p =0.019, see Figure 3b). Error bars on the figures present standard error of the mean. Pairwise comparisons for frustration were made with Wilcoxon tests. We found a statistically significant difference: visual cues were more frustrating than cues with the eyeglasses (p = 0.008) or the seat (p = 0.033).Other items in NASA-TLX were not statistically significant; however, the difference in physical demand approached statistical significance (p = 0.058, Figure 3c) as did the total NASA-TLX score (p = 0.076, Figure 3d). In both cases, these near-significant results favored the haptic cues versus the visual cues and haptic eyeglasses got the most favorable scores.

C. Reaction times, numbers counted, navigation errors

We used one-way repeated measures ANOVA and Bonferroni-corrected post-hoc pairwise comparisons to analyze the reaction times in the navigation task. ANOVA showed statistically significant differences between conditions (p = 0.001). The results showed that compared to the visual text cues, participants reacted 470 ms faster using the eyeglasses (p = 0.014) and 390 ms faster using the seat (p = 0.042) (Figure 4a).

Numbers counted were analyzed using Friedman tests. Counting errors were subtracted from the number count. No statistically significant differences were found in the correctly counted numbers (p = 0.266, Figure 4b) or in the navigation errors (p = 0.193, Figure 4c). The participants managed to count 39-41 numbers on average during the drive depending on the condition.

Navigation errors were also analyzed using Friedman tests. Errors in pressing the wrong button and choosing the wrong lane were added together: there were 9 congruent and 5 non-congruent errors (14 out of 576). All of the non-congruent errors were errors where the participant pressed the wrong button but chose the right lane afterwards. This happened only with one participant and only in the seat condition. The amount of errors was fairly low in all of the conditions (visual 1%, seat 4.2% and eyeglasses 2.6 % of turns). After deducting the non-congruent errors, the error percentage for the seat was 1.6 %. Four of twelve participants made a navigation error with the haptic cues, while one participant made an error with the visual cues.

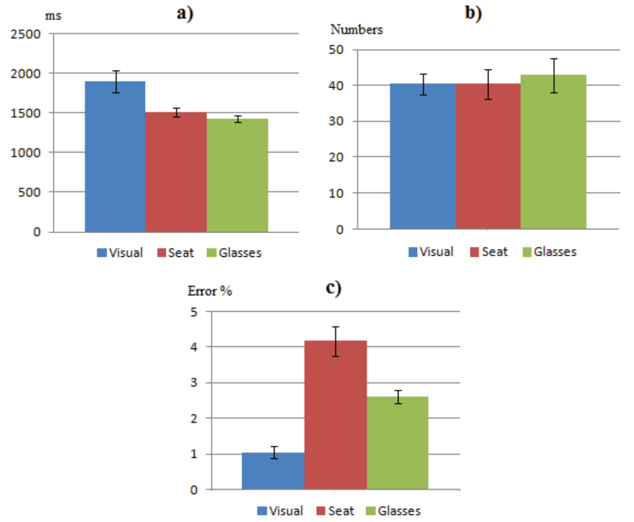

Figure 4. (a) Reaction times. (b) Number count. (c) Navigation error percentages.

IV. DISCUSSION AND CONCLUSIONS

We presented an experiment which shows that haptic cues with eyeglasses and a seat were processed faster than visual text cues. Haptic directional cues may thus have a lower cognitive demand than visual text cues. In other words, it could be argued that directional haptic cues are more intuitive than a visual display. The haptic cues were also experienced less frustrating than the visual cues. Many participants said that the visual cues made driving harder as you have to concentrate on the navigation instructions, which may explain the frustration. The results are in line with a study [28] that reported faster response times and lower frustration in target acquisition and robot navigation tasks with tactile vs. visual display.

There were no significant differences in the counting task or navigation errors. One way to interpret this is that although they exist, the differences of cognitive demand in the different conditions are small. As the cues were shown every 8 seconds on average while counting was done for the whole duration of the task, performance differences might be too small to observe. The opposite might be true for the navigation errors: with a large enough sample, haptic cues might result in significantly more errors than visual cues. This is due to their temporal nature and human error: in cognitively demanding situations, some cues will be inevitably missed.

The haptic directional cues were subjectively preferred: 83 % of the participants preferred the haptic cues to the visual cues. In addition, 83 % of the participants said they would use directional haptic cues alone or combined to other modalities. Similar results in subjective preference have been obtained in a study with soldiers [29]; comparing visual, audio and tactile navigation, 67 % of the soldiers preferred a tactile display. In this study, out of those who preferred the haptic cues, 70 % preferred the eyeglasses. Out of all participants 75 % could imagine using the haptic seat while the number for the eyeglasses was 58 %. The results are similar to an earlier study [10]: haptic cues are widely preferred over visual text cues, they are reacted to faster and subjective workload is somewhat lower. However, the same study showed that haptic cues are also prone to errors and the counting task showed no differences in workload. All in all, the results are mixed as in previous studies [4].

The eyeglasses were more preferred, rated less frustrating, less physically demanding and also had a lower total workload than the seat (Figure 3), although all findings were not statistically significant. The eyeglasses did also slightly better in reaction times, the number counting task and the total amount of navigation errors compared to the seat (Figure 4). All results favored the eyeglasses over the seat except for two: use in practice (58 % vs. 75% of the participants) and congruent errors (5 vs. 3).Based on the comments of the participants, a major problem with the eyeglasses was not the haptic cues but the prototype. Some participants found the eyeglasses uncomfortable to wear and not practical. None of the participants wore eyeglasses in their daily life which may have affected how they experienced wearing them. Specifically, the eyeglasses put pressure on the nose which can feel uncomfortable for some people. These things should be taken into account when interpreting the results. It would be interesting to run the same test with participants who habitually wear eyeglasses.

This study has a few limitations. First, the participants were young university students who did not wear eyeglasses and therefore do not probably present the whole driving population. Secondly, the study only included a high cognitive load condition so the findings cannot be generalized to low load conditions which might have different results. Thirdly, the study was done in a laboratory environment that lacks many of the things in real driving environments which burden the driver's attentional resources. Fourth, there are some unanswered questions about the visual cues as text cues might differ from more widely used arrow symbols in terms of processing speed. This issue affects the generalizability of the results and should be considered in possible future studies.

Navigating the environment consists of more than just left-right turns. Directional cues probably require other modalities to support them in practice. Combining the haptic cues with visual cues was mentioned many times in the interviews. This could be a promising approach. Directional haptic cues could be used to replace audio cues in situations that require instant responses. For instance, when driving a road and the approaching intersection is already in the driver's field of vision. There are two benefits compared to current audio systems. Haptics capture attention better than audio in noisy environments and directional cues guide visual attention effortlessly to the right direction [8]. The cues could increase driving safety in situations that are demanding on the visual and auditory senses, as driving in new and noisy environments. There are some design implications for audio and visual cues also; they could be located on the same side as the turns are.

The paper focused on car navigation but it is possible that haptic eyeglasses would work for other types of navigation (e.g. pedestrian, cycling) as well as for notification and warning purposes in general. Haptic cueing in the head area has mainly been studied for military applications but it can also work for civilian purposes. Haptic smartglasses could be one way to seamlessly combine car navigation to pedestrian navigation. Smartglasses may become increasingly popular in the future with technological advances. This study suggests that haptic navigation with eyeglasses functions well and motivates future research on the topic.

ACKNOWLEDGMENT

We wish to thank all the people in TAUCHI who helped with the study preparations and provided comments on the paper.

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Paper IV

Nukarinen, T., Kangas, J., Špakov, O., Isokoski, P., Akkil, D., Rantala, J., & Raisamo, R. (2016). Evaluation of HeadTurn: an interaction technique using the gaze and head turns. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (article 43). ACM. https://doi.org/10.1145/2971485.2971490

Evaluation of HeadTurn - An Interaction Technique Using the Gaze and Head Turns

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ABSTRACT

Smart glasses equipped with eye tracking technology could be utilized to develop natural interaction techniques. They could be used to conveniently interact with an electronic appliance in the environment from a distance. We describe a technique, HeadTurn, that allows a user to look at a device and then control it by turning the head to the left or right. We evaluated HeadTurn using an interface that linked head turning to increasing or decreasing of a number shown on a display. The task was to adjust then number to a given value. We studied the optimal rate at which number should change once the angle of head turn exceed a predefined threshold. We varied the rate of change of the number (217, 290, and 435ms per change) and the feedback (visual, haptic+visual). In the haptic condition, a 20 millisecond vibration was given through vibrating eye glass frame with each number change. Participants completed number selections faster with shorter intervals but also overshot the target more often. Seven out of 12 participants preferred the middle number changing speed (i.e., 290 ms). There were no statistically significant differences in task completion times. The optimal change rate of the numbers seems to be a compromise between faster selection and overshooting. Haptic feedback made the interaction slightly faster but the difference was not significant. The participants rated their experience with the technique as positive in general.

NordiCHI '16, October 23 - 27, 2016, Gothenburg, Sweden

ACM 978-1-4503-4763-1/16/10…$15.00
DOI: http://dx.doi.org/10.1145/2971485.2971490

Author Keywords

Gaze tracking; gaze-based interaction; haptic feedback; head moves

ACM Classification Keywords

H.5.2. User interfaces: Input devices and strategies

INTRODUCTION

When people select an object for manipulation, be that on a display for virtual objects or real world objects in the environment, they will usually start by directing their attention to the object. In practice this often means looking at the object of interest. Therefore, gaze-based pointing is a natural selection tool in human-computer interaction. Implementing gaze-based pointing requires that the target of gaze can be automatically identified.

For long, researchers have studied how to utilize gaze-based interaction (e.g. [28, 8, 22, 12]). Users with disabilities have been a small, but important user group for gaze-based interaction techniques. It has also been recognized that situational impairment makes everybody a potential user of gaze-based user interfaces in some mobile situations. For example Sibert et al. [22] state that: *"Eye gaze interaction is a reasonable addition to computer interaction and is convenient in situations where it is important to use the hands for other tasks."* Another potential usage scenario is when controls are visible but out of reach.

Besides physical and situational impairments, well-built gaze-based interaction may be motivated by convenience. Gaze tracking enabled glasses could be worn almost all the time. Reaching a pocket for a mobile phone or finding the TV remote control unit is often more difficult than gazing to initiate a control sequence.

Gaze-Based Interaction

The gaze tracking equipment is becoming more widely available and more affordable [6], making it possible to utilize it in everyday interaction with computers (see, for example, the Tobii EyeX[1]). Wearable gaze trackers are more difficult to design and somewhat more expensive, but they also are becoming more affordable [14].

The research on gaze-based interaction is increasingly focusing on the mobile environment [18]. It is expected that gaze interaction with mobile devices could partially compensate for some of the problems in designing user interfaces for small devices. However, practical implementations of gaze trackers built into mobile devices are not yet available. One of the reasons is that the visual cues that allow measuring the eye ball orientation precisely are so small that very high camera resolution and good lighting are needed for remote gaze tracking. Eye tracking glasses have an advantage in that the cameras can be placed much closer to the eyes. Thus, a tracker in the glasses can fairly easily measure the orientation of the eye ball. A head mounted tracker, however, needs to also observe the world via a forward-looking camera and identify interactive objects, map the gaze point onto these objects, and connect to them to interact through a wireless network.

Instead of building such a smart tracker, the alternative is to build an eye contact sensor in all objects. It has been shown [23] that such sensors are relatively simple to build. However, embedded eye contact sensors only allow eye contact detection, whereas smart eye tracking glasses allow many other uses of the gaze in addition to it.

Gaze-based input can be used in (at least) two roles (see, for example, Huckauf and Urbina [7]). The first is to select the object to be controlled by looking. The second is to initiate a command by gaze. There are several possible methods of giving commands by gaze. The best known methods are based on dwell time [28] or gaze gestures [4]. Object selection is natural and straightforward. Looking at the object of interest is a natural part of the behaviour when orienting one's attention in preparation to interact. Giving commands via eye movements is more problematic because gaze-based interaction with objects is not a part of our usual behaviour. Regardless of how the interaction technique is built, it will be somewhat artificial and needs to be learned. Dwell time has been extensively studied [15] and it is in general use. Gaze gestures are less used but in theory they offer a benefit of not requiring as accurate gaze tracking as dwell based methods [10, 21].

Regardless of the way that the interaction is implemented, in purely gaze-based user interfaces the gaze will have a dual role (observe and interact). Because of this systems where the object of interest is selected by gaze (looking) and then manipulated by other methods have been studied. The manipulation can be triggered in various ways, for example using a keyboard [12] or doing finger gestures on a handheld touch device [26, 27]. These techniques are probably the most efficient approach when a separate physical interaction device is available. The work in this paper relates to developing techniques for situations where it is more convenient to interact using the eye tracker data only. We are thinking of short interactions like turning on the TV or another appliance, adjusting the volume setting on speakers, fine-tuning the lighting in a meeting room, opening a locked automatic door when carrying the groceries, etc.

[1] http://www.tobii.com/en/eye-experience/

Head based control

Head movements are also a part of everyday life. Nodding and head shaking are universally used gestures (albeit with different meanings in different cultures). These gestures are already present in infants aged 13-18 months [11]. If we use movement patterns similar to these gestures, we will probably develop better interaction solutions than with less natural techniques.

Head movements have been studied intensively as a means for interaction, especially for controlling devices by disabled users (see for example [2, 5, 13]). Crossan *et al.* used head tilting for interaction in mobile situation for able-bodied participants [3]. None of these studies included gaze tracking, though. Mardanbegi *et al.* [16] and Špakov and Majaranta [25] studied object selection based on simple head gestures (gazing an object and using head nodding, head turns and head tilting for selecting). To our knowledge these are the only studies where gazing was used together with head move detection to implement an integrated control method. Špakov and Majaranta [25] studied head movements only to trigger an action while gaze was used for pointing, while Mardanbegi *et al.* [16] studied also a continuous control, changing the volume on a tablet interface by a head tilt[2]. Following Mardanbergi *et al.* [16] we suppose that the control method is indeed capable of serving also for more complex interaction that would extend beyond simple triggering.

Špakov *et al.* [24] corrected the cursor position by head movements in a continuous way (similar to Jalaliniya *et al.* [9]). The larger the head turn, the larger the cursor offset from the position returned by the tracker. The work in this paper can be seen as an extension for controls of the techniques by Špakov *et al.* [24] and Jalaliniya *et al.* [9]) and adding to the existing work by Mardanbegi *et al.* [16].

Haptic Feedback

Good feedback is especially important in gaze-based user interfaces because the natural feedback from eye movements is poor in comparison to manual operation of user interfaces. Visual feedback is the usual method with most systems that have a display. In some cases an audio feedback can be used, to replace the visual feedback or to complement it. While these two modalities cover most of the use cases, in some situations they can not be used (no display, distractions for gaze, too much noise, too quiet). A haptic feedback, based on the sense of touch is then a good alternative. We included haptic feedback in our experiments because earlier results [1, 10] showed that haptics can sometimes improve gaze-based interaction by making it more efficient and pleasant.

[2] From the paper we assume that the amount of tilt is directly used to define the amount of change in volume.

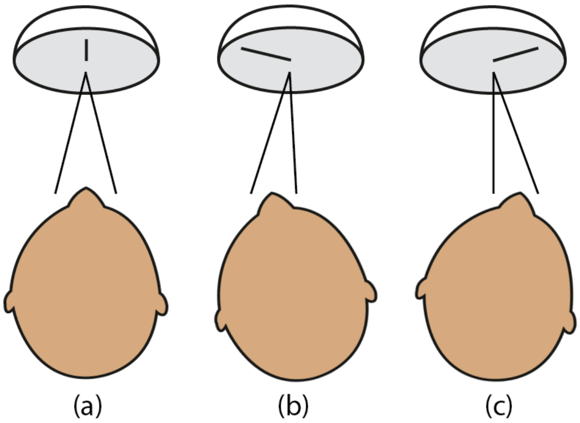

Figure 1. The operating principle of the HeadTurn technique illustrated with a volume control. The output volume of a sound system is changed by first gazing the control such as a speaker (a) and then while keeping the gaze on the control turning the head either left or right (b, c).

INTERFACE CONTROL BY GAZING AND HEAD TURNING

The new interaction technique, HeadTurn, is based on a gaze tracker that can be used also to sense the head orientation relative to the gaze direction. The idea is that the user of the technique will gaze on a control (that can take any form) and then turn his/her head either right or left to change the value of the associated control parameter, as illustrated in Figure 1.

The technique is analogous to a rotary control. Gazing at the control is analogous to touching the rotary knob. Turning the head while keeping the gaze on the control is analogous to turning the hand while it is in contact with the knob. If the user stops gazing the control (removes the hand from the knob) the head turn stops to have an effect on the control.

The head turn could affect the controlled parameter in various ways. The most obvious method is a "direct" control, where the angle of the head turn is directly translated to a new value. This seems to be the method that Mardanbegi *et al.* [16] experimented with. For example, if the original parameter value at the start $t = 0$ is A_0 and the angle of head turn (relative to the original direction at the start) is α_t, the new parameter value would be $A_t = A_0 + \beta\alpha_t$, where β is a scaling factor. Another simple method would be a "variable speed"-based control where the parameter's change speed would be controlled by the angle of the head turn. For example, if the original parameter value at the start $t = 0$ is A_0 and the angle of head turn at time t is α_t, the updated parameter value would be $A_t = A_0 + \sum_{i=0}^{t} \gamma\alpha_i$, where summation starts from the time of gazing, summation terms are observed at regular intervals and γ is a scaling factor. In both methods the adjustment is stopped by moving the gaze away from the control.

A variant of the latter method ("constant speed") is to translate the head turn angle to a fixed change speed using a step function. Employing such a step function requires users to first make a sufficiently large headturn ($\alpha_t > \alpha_{threshold}$) and hence it is tolerant to small head turns that might happen involuntarily or by accident. In this case the new parameter value at time t would be $A_t = A_0 + \sum_{i=0}^{t} s_i$ where change speed s_i is defined in Equation 1 by head turn angle α_i.

$$s_i = \begin{cases} \delta, & \alpha_i \geq \alpha_{threshold} \\ -\delta, & \alpha_i \leq -\alpha_{threshold} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

We experimented informally with different mapping functions and found both "direct" control and "speed" control functional. They have different strengths and weaknesses. Both also vary in usability depending on the mapping function employed. The "direct" control method allows very quick movements across different values, but the resolution (how many values can be separated) is limited by the accuracy of the tracking for head turn. Under noisy tracker data it can be annoying to try to hit a specific spot in the adjustment range. The "variable speed" mode allows fast movements, but requires a careful control when approaching target value. The "constant speed' with sufficiently high threshold and low speed is very robust to tracker noise, but frustratingly slow in moving across long distances.

Feedback

In all interaction a timely and topical feedback is important [19] for efficiency. HeadTurn will naturally generate feedback in various ways, depending on the task that it is utilized for. For example, if the controlled parameter is an audio volume, the change in the volume is an obvious feedback. Similarly a change in any visible parameter is a feedback. The system may also be augmented with additional feedback to emphasize the act of control. For example, tick sound at specific intervals, or graphics showing the present setting on the range of possible settings. In the studies described in this paper we used haptic feedback. The details of the feedback methods that we used will be described below.

THE EXPERIMENT: SELECTING A NUMBER

The goal of our experiment was to measure user performance and usability of the HeadTurn technique in one of the simplest configurations. Based on these results we would be able to conclude if further work would be worthwhile. The "constant speed", being a simple method and modified as described below, was the value control mode in this experiment. The optimal speed value δ of the step function was not known. We made it an independent variable in the experiment to find the optimal value.

The task given to participants was to repeatedly find and select a given target number using the HeadTurn technique. We created an application where the user would see a number that s/he can increase by gazing it and turning his/her head to the right and decrease by gazing the number and turning his/her head to the left. A screenshot of the application is shown in Figure 2. The target number was shown above the controlled number. Below the controlled number there was another box that the participant had to look at to confirm that s/he had found the target number.

When the participant was gazing the number and turned his/her head far enough to either side the controlled number would start changing. The first change would happen immediately

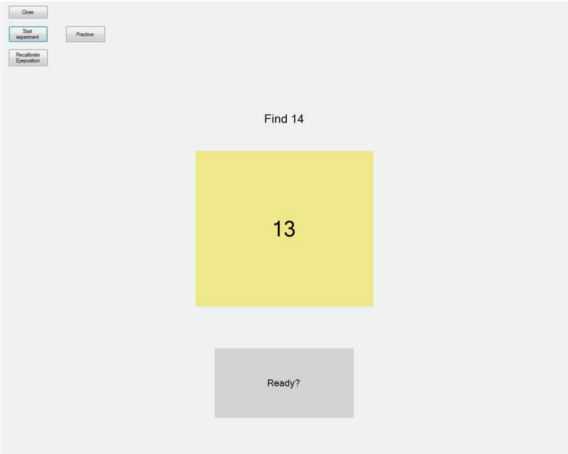

Figure 2. Screenshot of the Experiment 1. The participant was expected to look at the middle box, at the number, and either increase or decrease the number by head turning to reach the target value, shown above the box. The participant confirmed the selection by looking at the box below.

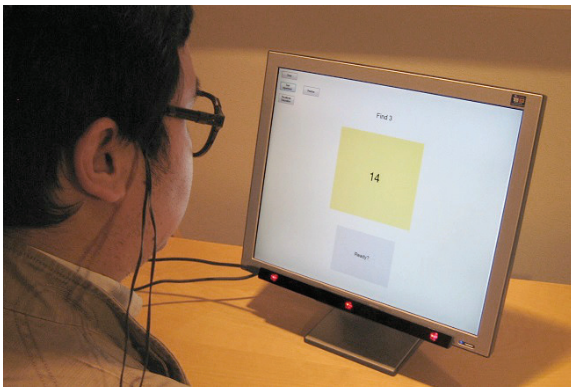

Figure 4. The experimental setup. The gaze tracker was attached to the bottom of the display. The haptic actuators were attached to the ends of the temples of the glasses. The participant was expected to look at the number in the middle box, and make that number match the target value shown above the box by turning his or her head. The participant confirmed the selection by looking at the box at the bottom of the display.

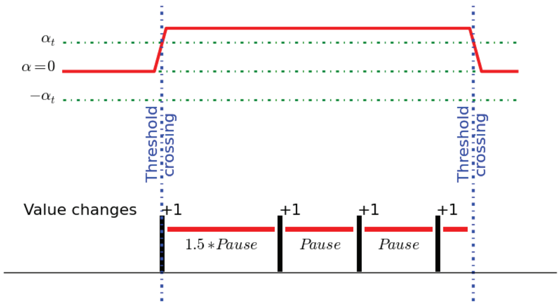

Figure 3. The schematics of the timing of value changes. The head turn angle (upper part of the image) is observed and as soon as the angle crosses either the upper threshold or the lower threshold the first value change is triggered. After that, as long as the angle stays on the other side of the threshold the value changes will be triggered with regular pauses in between, except that the first pause is 1.5 times the length of the regular pause. As soon as the head turn angle comes back to the neutral area the value changes will be stopped.

when the head turn angle exceeded the threshold value. After that the next changes would happen when the time from previous change would exceed a set time interval. However, the first time interval that followed the first change was 1.5 times as long as the regular time intervals to make it easier to change the number by one. Adjustments by one were especially important when participants overshot or undershot the target. As soon as the participant turned his/her head back (head turn angle below the threshold) or would look elsewhere from the control the number changing would stop. See Figure 3 for schematics of the value change timing by head turns.

The length of the time interval between the number changes was the first independent variable. The presence of haptic feedback was another independent variable. The haptic feedback consisted of a haptic pulse that was given at the same time as the number was changing. Haptic feedback has been used successfully as a confirmation in other gaze-based interactions (e.g., in [10]) and we wanted to find out if it had any effect on this new technique.

Participants

We recruited 12 participants (6 male, 6 female) from the university community. The mean age was 33. All had a normal self reported sense of touch. The participants had normal or corrected to normal vision but seven of the corrected vision participants did not wear corrective eyeglasses during the test. The reason was that the haptic actuators were attached to an eye glass frame. Wearing their own glasses and the haptic frame was not practical in most cases. All participants confirmed that they saw the task display well enough even without their glasses. Nine of the 12 participants had used gaze tracking applications before this experiment.

Apparatus

We used Tobii EyeX[3] gaze tracker to collect gaze data. The tracker was attached to a separate 19 inch display where the application was shown (see Figure 4) The experiment software was a Microsoft Windows form application built using .NET 4.5 framework running in a PC with Windows 7.

The EyeX Engine[4] provides the gaze coordinates on display that we used to detect if the participant was looking at the middle box. We used the eye position in the tracker's camera view to estimate the head turn angle in a manner similar to Špakov *et al.* [24, 25]. Although this position does not represent the head turn angle, it is linearly proportional to it when the angle is small. To keep the angle estimation correct, we instructed our participants to minimize their lateral head movements during the experiment, and to use rotational head movements only when they were changing the number.

The haptic actuators used in the experiment were attached to a glass frame (see Figure 4), similar to the one used by

[3] http://www.tobii.com/en/eye-experience/eyex/
[4] http://www.tobii.com/en/eye-experience/dev/eyex-engine/

Rantala *et al.* [20]. The haptic stimulus was felt behind the ears where the glass bows touched the skin. The total weight of the glasses was 23 grams. Tactile stimulation was given using Minebea Linear Vibration Motors (LVM8, Matsushita Electric Industrial Co., Japan). Pure Data (PD) software and a Gigaport HD USB sound card were used to create the audio signals sent to the actuators.

Haptic Stimuli

The actuators were driven using a 150 Hz sine wave. 150 Hz is the upper limit of comfortable vibration frequency in the head area [17]. The duration of the signal was set to 20 ms so that the perceived sensation would resemble a tap, and not be felt as vibration. The chosen stimulus duration was found long enough to be felt by all participants in pilot testing.

Experimental Design

The experiment consisted of six different blocks, 20 trials each. There were three different number changing time intervals, 217 ms, 290 ms, and 435 ms, with two feedback conditions, either haptic feedback or no haptic feedback (a 3x2 design). The corresponding maximum number change frequencies were 4.6, 3.45 and 2.3 changes per second. The fastest speed was chosen in the pilot tests so that it would be almost too fast for practical use. The slowest and middle speeds were 50% and 75% of the highest frequency.

The test was counterbalanced so that each participant got a different order of the trials. There were exactly 6 ways to order the timing conditions and two orders for the haptic/no haptic blocks. The trials with the same number changing speed were always done one after the other, but half of the participants would start with haptic and the other half with no haptic feedback.

Trial completion times and the number of corrections were recorded for each condition. The trial completion time was measured from when the target became visible to when the gaze entered the confirmation box. Then number of corrections was computed by subtracting the minimum amount of number changes (110) from the observed number change count.

We used a nine point bipolar Likert scale (-4 to 4) for the subjective evaluation of the technique. After each block the participants assessed the technique on five or six scales (see Table 1). A final survey was given after all the blocks. It included one Likert scale item of pleasantness or unpleasantness of the haptic feedback produced in the tests and a forced choice to choose which number changing speed they preferred. Finally, the participants were asked to write their comments on the haptic feedback and preferred number changing speed.

Procedure

The session began by briefing the participant on the purpose of the experiment. Then a consent form and a background information form were completed. The participants were seated in front of a monitor with an eye tracker. The distance to the monitor was approximately 30-50 cm. The eye tracker was calibrated and the participants were familiarized with the head turning technique. It was emphasized that a small head rotation is all that is necessary to change the numbers and that they should try to avoid any extra movements during the trials. During the introduction each participant tested the task with haptic feedback to get a grasp of the technique.

The experimental task was completed as described above. The target numbers in a block of trials included all numbers from 0 to 20 in a random order excluding 10 which was the starting number. Before each block of trials the participants first completed 5 practice trials identical to the actual test trials. After each block the participants rated it. The procedure described was repeated for all the six test blocks. For each participant the experiment took in total around 40 minutes.

Attribute	Extremes
Successfulness	poorly - well
Easiness	hard - easy
Pleasantness	unpleasant - pleasant
Practicality	impractical - practical
Number changing speed	too slow - too fast
Haptics (if present)	disadvantageous - advantageous

Table 1. Questionnaires in Experiment 1.

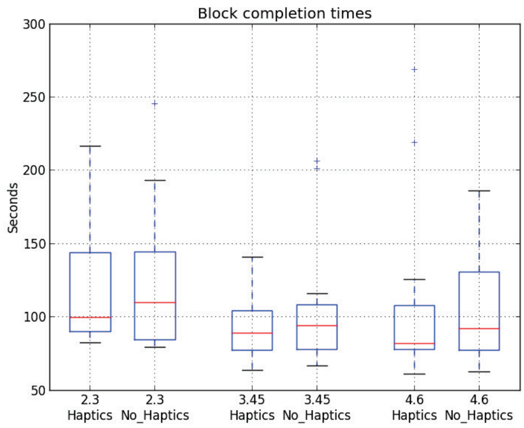

Figure 5. The block completion times in the Experiment. Completion times were slightly higher without haptic feedback, but not significantly so. The number changing frequency is shown below each column, as well as the haptics condition. The completion times with middle speed were about the same as with the highest speed.

Results

Objective measurements

Block completion times (sum of all trial completion times) and average times per number change were used for analysis. The block completion times (shown in Figure 5) varied naturally with the different number changing frequencies. The block completion times when haptic feedback was given were slightly shorter than without haptic feedback, but no significant differences were found (ANOVA).

The average time for a number change is shown in Figure 6. The tendency towards faster actions with higher frequency is

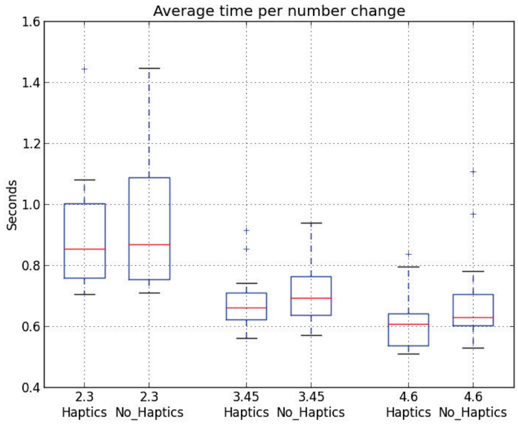

Figure 6. The average time per number change in the Experiment.

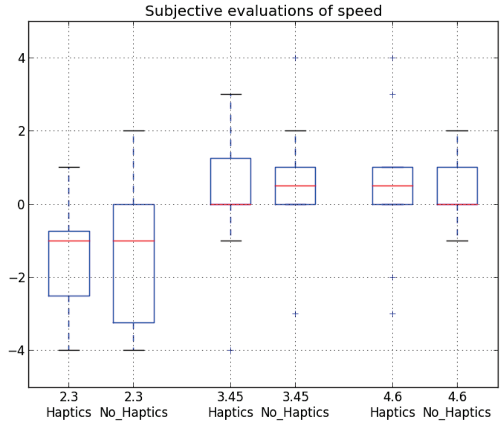

Figure 8. The subjective evaluation results of "Speed". The evaluations of both of the slowest number changing speed conditions differ significantly from all other conditions. The scale is from "too slow" -4 to "too fast" 4.

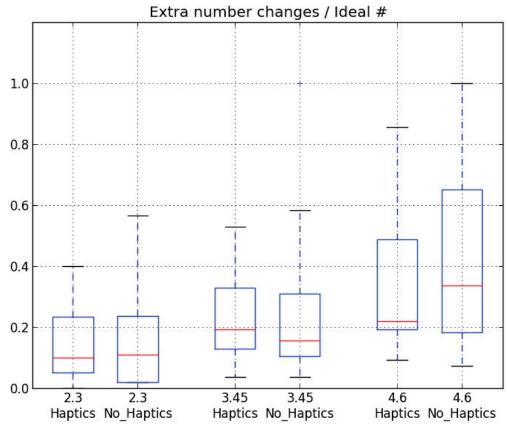

Figure 7. The ratio of extra number changes to the minimum number of number changes needed (110). For example, for 10 extra number changes the ratio would be $10/110 = 0.09$. The amount of extra activity grew with increasing number changing speed.

clearly visible. Again, there were no significant differences between the haptic conditions (ANOVA). The number of corrections per block is shown in Figure 7. The median number of corrections increases with increasing number changing frequency.

Subjective results

The participants' overall experience of the head haptics was positive (median 2, mean 1.6 on a -4 to 4 scale). Eight of the twelve participants made positive evaluations of the head haptics while two made negative and another two made neutral evaluations. Seven of the twelve participants preferred the middle number changing speed the most, three preferred the fastest, one the slowest, and one could not decide.

Questionnaire answers were not significantly different between the conditions except in one case. This was "Subjective evaluation of speed" (Friedman test, $p < 0.001$). The two conditions with the lowest number changing interval resulted in lower evaluations (Wilcoxon paired-samples test, $p \leq 0.05$) in all cases than the four conditions with faster intervals (see Figure 8). Most of the participants felt that the slowest speed was too slow for the purpose.

Free form comments

Eleven of the twelve participants said that the haptic feedback was helpful, useful, functional or appropriate for the tasks in some way. Six participants mentioned some negative aspects of the feedback, mainly the excessive amount of haptic stimulation and delayed haptic feedback in higher number changing speeds.

In free-form comments the middle number changing speed was described as the most precise (4 participants). It was also said to be the most versatile speed (2 participants) as it works with or without haptic feedback and is good for small and large distances. The slowest speed was said to be too slow (4 participants) although one participant preferred it for its precision. The fastest speed was liked by some because the slower speeds were experienced too slow (2 participants).

DISCUSSION

With increasing number change rate, the task completion time naturally decreases. However, overshooting the target value also becomes more common when speed increases. The overall best results are a compromise between these two factors. While the block completion times varied slightly the two factors almost balance each other; there were no significant differences in the block completion times.

The subjective evaluation indicated that the middle speed in the experiment was the most preferred. Seven out of twelve participants mentioned it as the most preferred speed. The slowest speed was judged too slow subjectively while number of error corrections seems higher for the fastest speed. Between them the middle speed was obviously a reasonable compromise.

Overall, most of the participants reacted positively to the haptic feedback. However, there were also some negative comments, and probably the implementation details should be revised. Important issues are, e.g. the responsiveness, to minimize any delays, and the amount/strength of haptic feedback to avoid annoyance.

Our experiment involved only adjusting integer values in a range ± 10. Instead of numbers the list that is traversed could contain anything. For example, it could be a menu containing commands. In such a case all menu items should be visible to make finding the desired item easier.

The same technique would probably work also with an auditory menu allowing the control of displayless devices. Based on the work by Špakov et al. [24] also two-dimensional control structures could be used. Speech input as well as input from handheld devices could be combined with HeadTurn to create even richer interaction possibilities. For instance, a crude selection of some parameter scale could be done by speech, e.g. looking an audio volume control and saying "loud". Then HeadTurn could be used to fine tune the selection, by looking the control and turning head slightly.

Overall, we see a wide range of further possibilities in this theme. However, additional work is required to refine the interaction technique for natural contexts, which are often mobile. More sophisticated implementations could benefit from machine learning and from developing algorithms based on user data. We emphasize that this study is mainly an initial proof of concept.

CONCLUSION

This paper has two main contributions. First, the gaze tracker based system built to control the parameter values in a given range worked well. The participants tended to rate their experience as positive and were able to complete all trials. This motivates further implementations and research in using head turn interaction with smartglasses.

Second, the selection tasks were completed slightly faster when the interval between number changes was shorter. On the other hand, the participants also overshot the target more with shorter intervals. As a good compromise, majority of the participants (7 out of 12) preferred the middle number changing interval (290 ms). Therefore, we conclude that 290 ms would be a good starting point for selection speed when designing head turn interaction.

ACKNOWLEDGMENTS

We thank the members of the research unit for providing helpful comments on various versions of this document. This work has been funded by the Academy of Finland, projects Haptic Gaze Interaction (decision numbers 260026 and 260179) and Mind Picture Image (decision number 266285).

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Paper V

Nukarinen, T., Kangas, J., Rantala, J., Pakkanen, T. & Raisamo, R. (2018). Hands-free Vibrotactile Feedback for Object Selection Tasks in Virtual Reality. *In Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology* (p. 94). ACM. https://doi.org/10.1145/3281505.3283375

Hands-free Vibrotactile Feedback for Object Selection Tasks in Virtual Reality

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ABSTRACT

Interactions between humans and virtual environments rely on timely and consistent sensory feedback, including haptic feedback. However, many questions remain open concerning the spatial location of haptics on the user's body in VR. We studied how simple vibrotactile collision feedback on two less studied locations, the temples, and the wrist, affects an object picking task in a VR environment. We compared visual feedback to three visual-haptic conditions, providing haptic feedback on the participants' (N=16) wrists, temples or simultaneously on both locations. The results indicate that for continuous, hand-based object selection, the wrist is a more promising feedback location than the temples. Further, even a suboptimal feedback location may be better than no haptic collision feedback at all.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; *Haptic devices*; *Pointing*; *Empirical studies in HCI*;

KEYWORDS

Haptic feedback, visual feedback, collision detection, object selection in virtual reality

ACM Reference Format:
Tomi Nukarinen, Jari Kangas, Jussi Rantala, Toni Pakkanen, and Roope Raisamo. 2018. Hands-free Vibrotactile Feedback for Object Selection Tasks in Virtual Reality. In *VRST 2018: 24th ACM Symposium on Virtual Reality Software and Technology (VRST '18), November 28-December 1, 2018, Tokyo, Japan.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3281505.3283375

1 INTRODUCTION

As virtual reality is gaining popularity, it is increasingly relevant to investigate how to augment VR environments with haptics. We propose that it would be fruitful to study if simple haptic feedback could improve the user experience and efficiency of commercially available VR systems where virtual hand/3D cursor-based selection techniques are the norm. Haptic feedback has been found to increase performance compared to visual only feedback in many contexts of use [1]. Cheng et al. [2] showed that adding vibrotactile feedback to visual feedback improved task completion times in a grasping task. Moehring and Froehlich [3] demonstrated that adding tactile grasping feedback improved interaction in a CAVE and in using a head-mounted display. However, previous research [4] indicates that even in VR the usefulness of haptics is situational. We propose that the location of the feedback could be one such situational factor.

The motivation of this study was to explore vibrotactile feedback in VR for two less studied body locations that do not require a hand controller. The main contribution is in evaluating vibrotactile collision feedback in the wrist, and the temples for proximal, hand-based object picking. Further, we demonstrate that in this specific context, the temples may be a suboptimal location for vibrotactile feedback.

2 METHOD

We explored the effect of vibrotactile collision detection feedback (i.e., feedback when the controller collides with an object) in an object picking act. There were four feedback conditions: visual only (*No Haptics*), haptic wrist (*Wrist*), haptic temples (*Temples*), and haptics on both the wrist and the temples (*Both*). We investigated if there are differences in user preferences or the speed of the interaction between the four feedback conditions.

16 volunteer participants (7 females, 9 males, mean age 37, SD 8.5, range 24-52 years) from the university community took part in a user experiment. Ten out of 16 participants had at least some earlier experience of VR technology. One participant was left-handed, and 15 were right-handed. Five out of 16 participants wore eyeglasses during the experiment.

We used a laptop PC, an HTC Vive VR headset, an HTC Vive hand controller and Unity Virtual reality development environment to set up the experiment. As vibrotactile actuators, we used Minebea Linear Vibration Motors (LVM8, Matsushita Electric Industrial Co., Japan). These actuators were chosen mainly because their small size enables flexible use in different locations. We vibrated the actuators by sending audio signals from Unity to a Gigaport HD USB sound card, which connected to an IMG Stage Line STA-1508 amplifier. The haptic actuators were attached to a Velcro wristband and the HTC Vive headset (Figure 1). As Figure 1 shows, the actuators were located on the upper side of the wrist and near the left and right

VRST '18, November 28-December 1, 2018, Tokyo, Japan

ACM ISBN 978-1-4503-6086-9/18/11.
https://doi.org/10.1145/3281505.3283375

Figure 1: One actuator was on the wrist (left). Two actuators were on the participant's temples (right).

Figure 2: The grey picking tray and the brown dropping container (left). The visual collision detection feedback (right).

temples when worn by a user. As haptic feedback, we used 30 ms vibrotactile stimulation driven using a sine wave with a frequency of 150 Hz. We utilized an object color changing visual feedback for the collision detection in all experimental conditions. (Figure 2, right).

A single trial consisted of moving sixteen randomized cubes from a tray to a separate container box (Figure 2, left) in a given order. The purpose was to move the controller over a cube, get feedback, press the controller trigger button to pick the cube, hold and move it over the container and drop the object by releasing the button. Each trial was repeated four times for each feedback condition. As we had four feedback conditions, the participants performed 256 ($16 \times 4 \times 4$) object picks in the experiment. The participants answered a questionnaire about their experience after the vibrotactile conditions using a scale from -4 to 4. Finally, we asked the participants to put the four conditions in preference order, and also explain why did they select the preferred method.

3 RESULTS

We analyzed six attributes of the vibrotactile feedback (control, arousal, pleasantness, effectiveness, strength, and timeliness) using Friedman tests, and did further pairwise comparisons with Wilcoxon tests. The Friedman tests showed statistically significant differences in the attributes control ($p = 0.014$), arousal ($p = 0.043$), pleasantness ($p = 0.017$), and effectiveness ($p = 0.004$). The tests did not show significant differences for the attributes strength ($p = 0.185$) and timeliness ($p = 0.819$). Bonferroni-corrected Wilcoxon tests showed a significant difference on the feeling of control between the conditions *Temples* and *Both* ($p = 0.045$), and between *Temples* and *Wrist* ($p = 0.036$). The participants felt more control in the conditions *Both* and *Wrist* than in the condition *Temples*. There was also a statistically significant difference on the feeling of arousal ($p = 0.027$), pleasantness ($p = 0.021$), and effectiveness ($p = 0.006$) between the conditions *Wrist* and *Temples*. The participants rated the wrist feedback as more arousing, pleasant, and effective than the feedback on the temples.

For the most preferred method, the order was *Wrist* (62.5 %), *Both* (19 %), *Temples* (12.5 %), and *No Haptics* (6.25 %). For instance, 62.5 % of the participants preferred the wrist condition the most. The order for least preferred method was *No Haptics* (62.5 %), *Temples* (25 %), and (*Both*) (12.5 %). We analyzed the differences on the rankings with a Friedman test and found a significant difference ($\chi^2(3) = 30.23$, $p < 0.001$). Bonferroni-corrected Wilcoxon tests showed significant differences on the preference order between the conditions *Wrist* ($p = 0.012$) and *No Haptics*, and between *Wrist* and *Temples* ($p = 0.024$). The wrist feedback was significantly more preferred than either no haptics or haptics on the temples.

The most common comments about preferred feedback concerned the wrist haptics and how it felt most natural or realistic (5 comments), and how touching the object with a hand was felt on the hand (4). Also, wrist feedback was described as noticeable (2), supporting visual feedback (2), and making the task easier (2). Concerning combined feedback, two participants mentioned getting better confirmation. Further, two participants mentioned they could not feel the temple feedback. One participant out of 16 preferred visual feedback without haptics (condition *No Haptics*). The participant said that she felt more focused and faster without haptics. The comments on haptics were generally positive, and the participants said they would prefer to use the haptic feedback with VR devices.

For the trial completion time analysis, we did not identify outliers and therefore used the average from the four trials. The data were normally distributed, so we analyzed it with one-way repeated measures ANOVA. There were no statistically significant differences between the conditions ($F_{3,13} = 0.19$, $p = 0.903$).

4 CONCLUSION

In sum, the wrist seems a more promising feedback location than the temples for continuous, hand-based object selection in a low cognitive load environment. We reason that temple actuation could be better for tasks with infrequent feedback, and when the tasks are closely tied to gaze and head movement behavior. Finally, the results suggest that a feedback location that is suboptimal for a task may still be a better choice than no haptic feedback at all.

ACKNOWLEDGMENTS

This work has received funding from the VARPU project (decision 1444/31/2016).

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http://www.uta.fi/sis/tauchi/dissertations.html.

1. **Timo Partala:** Affective Information in Human-Computer Interaction
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